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ADVANCED SIMULATION IN UNDERGRADUATE PILOT TRAINING: MOTION SYSTEM DEVELOPMENT

G. J. Kron

Singer Company

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ADVANCED SIMULATION IN UNDERGRADUATE PILOT TRAINING: MOTION SYSTEM DEVELOPMENT

By

G. J. Kron

Singer-Simulation Products Division
Binghamton, New York 13902

ADVANCED SYSTEMS DIVISION
Wright-Patterson Air Force Base, Ohio 45433

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AIR FORCE SYSTEMS COMMAND

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The production of kinesthetic information pertinent to the aircraft piloting task by use of motion base devices relies on mathematical models which are developed in a largely empirical manner and evaluated in a subjective manner. The ASUPT simulator contains a motion math model which is developed in analytical fashion and permits broad latitude for experimenter input to alter or degrade the resultant motion information. This permits research that is useful in establishing a relationship between the amount and scope of motion information and training value. The motion system employed is a 60-inch six-degree-of-freedom synergistic system. It is driven in translation by a model which permits passage of acceleration onset information followed by controlled velocity and position

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washout. Rotational information is controlled by digitally implemented cue shapers, and sustained translation acceleration simulation is made available by subliminally tilting the motion system platform to cause a projection of the gravity vector to be aligned with the sustained force. This report discusses the implementation of these concepts, and forms a foundation for understanding the ASUPT motion system computer programs.

SUMMARY

PROBLEM

The advanced simulator for undergraduate pilot training is a research device designed for investigating the role of simulation in the future undergraduate pilot training (UPT) program. For ASUPT to be effective in training research, it must faithfully simulate all aspects of flight, including extra-cockpit visual cues and motion and force cues.

The selection of the ASUPT motion system was based upon the following requirements: (1) representative motion caused by ground roll, ground acceleration, braking, differential braking, buffets, skids, slips, banks, climbs, dives, rolls, touchdown attitude and impact, rough air, wind, gust conditions, and control-induced changes in the exterior configuration of the vehicle must be simulated, and (2) the math model which drives the motion system hardware must be flexible with respect to change and experimenter control.

APPROACH

In order to satisfy all of the possible motion requirements in the UPT regime, which includes aerobatics as well as taxiing and other ground work, the six degree-of-freedom (dof) synergistic motion system was specified.

The six dof motion system allows for movement of the simulator flight compartment about the z-axis (vertical and yaw), along and about the y-axis (lateral and pitch), and along and about the x-axis (longitudinal and roll).

Since it is impossible to duplicate complete aircraft motion, the system provides onset accelerations which are removed at the subliminal level to provide the representative physical sensations of motion.

RESULTS

Two six dof motion systems were developed and integrated with the ASUPT basic simulators. In meeting the above requirements, the ASUPT motion drive scheme is the only Singer-SPD motion package configured such that platform acceleration during the onset cue phase very closely matches the aircraft acceleration in magnitude and shape. The motion systems and cockpits with visual displays were installed at AFHRL/FT, Williams AFB, Arizona in September 1973. The fully integrated ASUPT system was accepted on 17 January 1975.

CONCLUSIONS

The ASUPT motion system is designed with a flexible model so that research concerning kinesthetic simulation may be conducted. The rotational cueing concept embodied in the ASUPT design represents a significant advance in motion simulation. Engineering research has been conducted with the ASUPT motion system, including system refinements as well as the development of new drive algorithms. The system will serve as a bench mark for future motion-based simulators.

PREFACE

This report is the 2nd of seven volumes describing the Advanced Simulation in Undergraduate Pilot Training (ASUPT) system development program. The seven volumes of AFHRL-TR-75-59 are as follows:

Volume I: Advanced Simulation in Undergraduate Pilot Training: An Overview

Volume II: Advanced Simulation in Undergraduate Pilot Training: Motion System Development

Volume III: Advanced Simulation in Undergraduate Pilot Training: G-Seat Development

Volume IV: Advanced Simulation in Undergraduate Pilot Training: Automatic Instructional System

Volume V: Advanced Simulation in Undergraduate Pilot Training: Computer Image Generation

Volume VI: Advanced Simulation in Undergraduate Pilot Training: Visual Display Development

Volume VII: Advanced Simulation in Undergraduate Pilot Training: Systems Integration

This project derived from a DOD Directive to the three Services requesting programs of advanced development in the area of training and education. The purpose was to insure that military training and education make the fullest use of recent innovations and technological advances. In October 1967, a joint Air Training Command/Air Force Human Resources Laboratory effort culminated in a recommendation to establish an advanced simulation system at an undergraduate pilot training base. Hardware development of the ASUPT began in 1971 and the system was released for research in Jan 75.

All members of the ASUPT Program Office and participating organizations who worked on the program contributed to the final system. In addition to the listed contract monitors, they include Don Gum, ASUPT Program Manager, James Basinger, CIG Project Engineer, Israel Guterman, Basic Simulators Project Engineer, William Albery, Systems Integration Project Engineer, Patricia Knoop, Advanced Training Systems Project Engineer, Kenneth Block, Program Controller, and Virginia Lewis, Secretary, all of the Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson AFB OH; Warren Richeson, Capt Frank Bell III, Maj Ray Fuller, Capt John Fuller, Capt Dennis Way, Capt Steve Rust, Capt Mike Cyrus, and Mr. Glenn York, all from the Flying Training Division, Air Force Human Resources Laboratory, Williams AFB AZ.

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INTRODUCTION

The methods b which man learns have long been the subject of research; the interim findings, observations, and theories have often been the subject of much controversy and argument. Fundamental agreement exists, however, that man must have contact with his environment; he must be aware of the stimuli about him and he must interpret them and act upon their informational content. An important portion of learning and training research, then, is directed at obtaining an understanding of how man relates to, and with, his environment.

Man's sensory systems are the interface between him and his environment; through these systems travel the raw information used in learning and in the maintenance of task proficiency. Considerable effort has been expended on assembling a knowledge of the operation of the various sensory systems, with various degrees of success, depending upon which sensory system is under consideration. The knowledge derived from the visual sense, for instance, appears to be more precise, more formalized, and less subject to question than that derived from the vestibular sense and, to a greater degree, the body awareness sense. Simulation, a technique employed for training, depends heavily on the role sensory systems play in the learning process.

Historically, the simulation devoted to providing stimuli to be used by a given sensory system appears to generally follow the knowledge existing at the time pertaining to that sensory system. Hence, the simulation of the visual scene, first in terms of cockpit instrumentation, and later the window visual scene, is quite sophisticated and refined. Stimuli for the vestibular and kinesthetic senses were provided through the use of various types of cockpit motion systems. Most recently, stimuli for sustained accelerations are being provided for in the development of G-seats.

Work continues in all areas of sensory simulation to determine which stimulus channels have priority within specific training tasks, and which seem to have low priority and do not noticeably degrade the learning process when omitted. Included in this effort is investigation of intra- and inter-sensory system cue reinforcement and the question of partial or total cue substitution. The investigation or the interrelationship of motion information available through the vestibular and the haptic, or "body feel", sensory systems has lent emphasis to the development of G-seat mechanisms suitable for producing the type of stimuli recognized by elements of the haptic sensory system and sophisticated motion systems for producing stimuli recognized by both the vestibular and haptic systems.

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SYSTEMS FOR MOTION PERCEPTION

It is helpful, at this point, to briefly discuss the elements of the system by which an individual perceives and evaluates the type of motion to which he is subjected. The sensory systems involved are not limited solely to the transmission of motion information. They are also involved in ascertaining the direction of gravity with respect to the head, the relative attitude of the skeletal structure with respect to that gravity vector, and the location of the surface of the flesh with respect to the skeletal attitude.

Man is thought to perceive motion through at least three basic sensory systems: they are the visual, vestibular, and haptic systems. The visual sensory system will not be discussed herein but is mentioned as one of the sensory systems entrusted with the important task of kinesthetic determination.

THE VESTIBULAR SYSTEM

An excellent description of the vestibular system appears in Modeling of the Human Force and Motion Sensing Mechanisms[1] by D. R. Gum, and the reader is urged to obtain this document to complement the information contained herein.

MOTION AND THE HAPTIC SYSTEM - Repeat of pgs. 7-9, AFHRL-TR-75-59 (III)

As mentioned earlier, the haptic system mediates the body feel of motion. It seems reasonable to assume that the greater the acceleration to which an individual is subjected, the larger or better defined the haptic system response. Of initial concern, then, are large sustained accelerations such as those found when a pilot of an aircraft performs a tight dive pullout.

Consider the dive pullout case in which a pilot is subjected to a "g" loading or increase in apparent body weight, proportional to the number of g's of acceleration experienced by the aircraft. Assuming the pilot is seated, we might expect his head, neck, and upper torso to compress along the spinal axis, his shoulders to droop under the "added" weight of his upper arms, and his buttocks to sink deeper into the seat cushion, thereby decreasing the included angle between upper and lower portion of the leg. In other words, his body orientation would change slightly due to the increase in apparent weight.

Further, we might expect our subject's flesh to droop and change the loading characteristics of the muscles and, corresponding to the increased apparent weight of upper torso, we would expect an increase in buttock flesh pressure. Vascular system pressure increases in the lower torso and legs would be experienced. and visceral effects of internal organ distention and body fluid pressure changes could also be expected.

Now, if the acceleration vector had significant components in the plane normal to the subject's spine, the subject would begin to react like an inverted pendulum. Head, shoulders, and upper torso would tend to pitch or roll about the lower torso, again changing skeletal attitude and muscle loading conditions, to say nothing of the obvious shift in eye point. Such pitching and rolling is significantly reduced through the use of lap belts and shoulder harnesses; however, these restraints do not remove the inverted pendulum effects of the head and neck, only partially restrain shoulder movement and, in general, introduce a new set of body points subject to touch and pressure sensation.

Haptic system elements are employed in perceiving these physiological changes. Most of these changes manifest themselves in one or more of four modalities: skeletal attitude changes, muscle tonal changes, pressure changes, and touch or area of contact changes. Considering first skeletal attitude changes, the older, more formalized theory advocates that joint receptors are interspersed throughout the ligaments and capsules of the skeletal joints and are responsible for monitoring the attitude of one bone structure with respect to its neighbors. The receptors themselves appear to be attitude-critical; at any given joint angle a particular set of receptors triggers the neural response, becoming more and more passive (adapting) until that particular joint angle is again approached, while other sets of joint receptors become active as the joint angle passes their particular critical stage. In this manner the attitude of the structure is perceived, via successive joint relations, relative to the spine, to the neck and head, and finally to a basic reference frame such as the gravity vector. Thus, the shift in skeletal alignment due to G loading produces an informational input in the kinesthetic evaluation process.

Not everyone subscribes to the presence of joint receptors. An emerging theory challenging the presence of joint receptors is predicated on the belief that joint attitude perception is the product of differentiation of pressure sensations resulting from deformation of the flesh surrounding the joint.

A second category of haptic system receptors are the receptors located in and around the muscles, which are generally thought to be of two types: the spindle and tendon receptors. The spindle receptors appear to possess two subsets of receptors. The more numerous primary set, characterized by annulospiral endings and located toward the center of the spindle, is sensitive to the rate of change of muscle length while the neural output of the secondary set, those with flower spray endings and located toward the ends of the spindle, appear to represent an instantaneous muscle length measurement. The second type of muscle receptor, the tendon receptor, appears to be a strain measurement mechanism for its neural output increases as does the strain on the muscle.

The total neural response in muscle contraction is characterized during the onset phase by high spindle output and low but increasing tendon output. As the strain increases and muscle movement slows, the response is characterized by high tendon receptor output and low spindle output.

As G loading increases, it appears that muscle tone changes owing to the increase in inertial weight of the tissue supported by the skeletal frame. Some muscles may relax and elongate; others are probably forced into contraction in an attempt to minimize tissue deformation due to the G load. One cannot help noticing the potential lateral and longitudinal acceleration sensing mechanism formed by the inverted pendulum condition of the head, neck, and shoulders coupled with their muscular restraint structures and associated neural feedback.

With respect to the third category, information on the perception of flesh pressure indicates that the pressure gradient existing over a given section of flesh is perceived, rather than the absolute magnitude of flesh pressure. There appears reasonably consistent agreement that the prime pressure-sensitive cell is characterized by the Pacinian Corpuscle situated in a deep flesh location. These cells are onion-skin-like laminations surrounding a nerve fiber ending. Deformation of this cell due to environmental pressure causes nerve impulses in the sensory fiber.

As the inertial weight of the torso increases due to increased G loading, the pressure gradient over the buttocks changes as the primary bone structure in this region, the ischial tuberosities, transmit loading to the surface of the seat. The flesh trapped between the ischial tuberosities and the seat is subjected to increased pressure and the pressure-sensitive receptors in this area respond.

Muscle and pressure receptors are not necessarily confined to locations in the external regions of the body but are likely responsible for perception of visceral and vascular system acceleration effects as well. Here the receptors are located deep within the body as a part of, or adjacent to, the internal organs and circulatory system components.

The fourth category of acceleration-induced physiological change mentioned earlier is that of touch, or area of contact change. Under increased G loading the subject settles deeper into the seat, bringing a larger portion of his buttocks and thigh flesh area into contact with the seat. A more informative way of stating this is that because of the acceleration environment more of the seat touched the subject's flesh; the subject did not actively seek to touch more of the seat. The receptor units of interest here are

those allied with the sense of cutaneous touch. These include a number of different types of receptor units, such as hair cell detectors and pressure receptors; however, the pressure receptors here are those located near the surface of the flesh and affiliated with cutaneous deformation sensation as opposed to the deep-flesh pressure receptors affiliated with flesh pressure discrimination.

Taken individually, the elements of the haptic system respond with information concerning the movement of the body due to G loading in a rather segmented manner. It appears that no one element provides the spectrum of information necessary to define what is happening to the body. Fortunately, it seems that haptic system element outputs are employed in a covariant manner to provide a more sophisticated definition of body position and motion. Further, haptic system outputs, at a higher order of sensory system hierarchy are merged in a covariant manner with vestibular and visual input to further refine this complex perception.

MOTION SYSTEMS AND THE VESTIBULAR AND HAPTIC SYSTEMS

What is a motion system? In its most general sense a motion system could be construed to be any prime mover which has the capability, though inertial and gravitational effects only, to disturb and ellicit a neural response from the vestibular and haptic sensory systems. An ocean wave, a vortex filament in air, a being's own movements could be considered a motion system. However, we are concerned with the vestibular and haptic system response arising from a very narrow and specific experience - that of piloting an aircraft.

An aircraft is a motion system. The aircraft carrier that rides the ocean wave is a motion system; but we are interested in yet a more specific aspect of piloting an aircraft and that is the training necessary to the pilot in order that his piloting performance be sufficient to satisfy his mission objectives. Piloting an aircraft is a control system task involving pilot response to observed conditions; kinesthesis is a portion of the spectrum of observed conditions. The vestibular and haptic systems help make this observation possible. Just as the reader, if he were to rise and walk to the door, makes use of the vestibular and haptic information stimulated by his body movements (his motion system) to control this most fundamental control task, the pilot uses like information stimulated by his aircraft movements to control the aircraft.

Our effort in the training environment is, in a ground based device, to produce within the trainee vestibular and haptic system information comparable to that existing in the actual task. The actual task motion system is the aircraft and its dynamic environment; in the simulated task the motion system is a device which moves, under very constrained conditions, the simulated cockpit and trainee in translation and rotation. The device employed by ASUPT is a six degree of freedom synergistic motion platform supported and driven by six 60-inch hydraulic actuators (figure 1).

The variation of actuator, hereafter referred to as "rams" or "legs", length produces platform motion in all six degrees of freedom. A given platform attitude and/or position can be achieved only through the definition of all six ram lengths. By determining what type of translational and rotational motion time history, hereafter referred to as a "profile", we wish to impose upon the pilot trainee, the ram lengths necessary to cause this motion can be computed by geometric relationship of the platform to its support, and then output to the hardware.

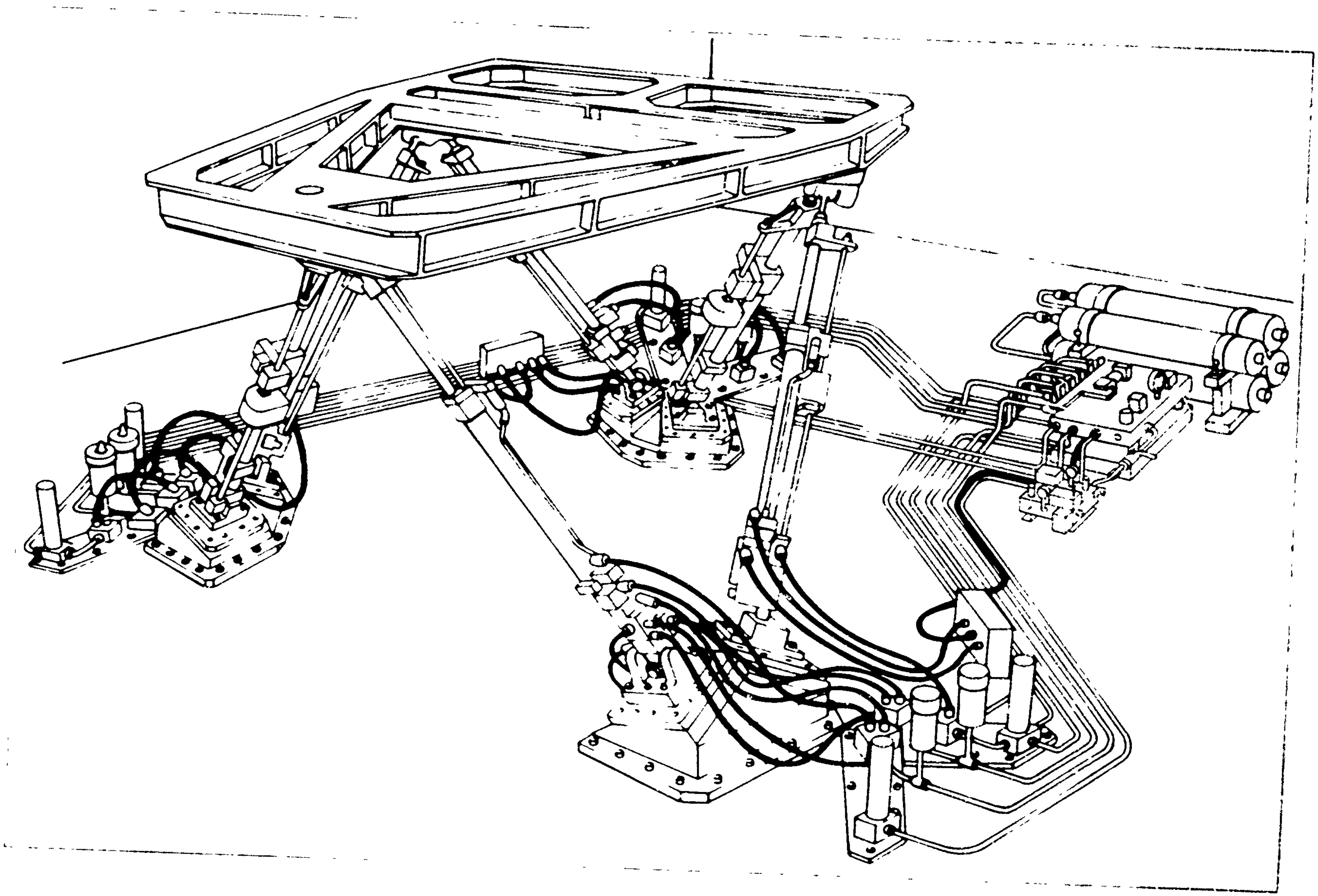


Figure 1. SIX-DEGREE-OF-FREEDOM MOTION SYSTEM

The motion system hardware servo loop has been found to be precise in tracking the type of ram commands of the frequency content associated with the above motion and employs its own monitor to guard against excessive tracking error. The software which drives the motion system could therefore operate in total open loop fashion with a fair degree of assurance that when a platform position and attitude is decided upon and so commanded through the rams, said position and attitude is promptly achieved.

For the time being then we will discuss motion in terms of desired platform translation and rotation much like we think of aircraft motion in terms of its positional and attitudinal changes.

Obviously if the motion platform and cockpit containing the pilot trainee can be translationally or rotationally accelerated and its attitude with respect to the gravitational vector altered, we can expect, based on our understanding of the vestibular system, to elicit vestibular neural response. Likewise, but receiving much less attention until recently, a comparable haptic system response will also exist due to the fact that the trainee's body inertially moves within the simulated cockpit much as it will move due to inertial effects while piloting the actual aircraft.

MOTION SIMULATION PROBLEM

If it were possible to cause the motion platform to duplicate the maneuvers of the aircraft in one to one correspondence, two conditions would probably exist: there would be little requirement to investigate motion simulation, and the duplicative device would be more costly to construct and operate than the actual aircraft. This cost factor plus the overall philosophy of simulation requires a motion base design which, compared to actual aircraft motion capability, displays extreme performance constraints. These constraints establish the requirement for motion simulation investigation for, since it is not possible to duplicate in one to one correspondence the actual motion environment, it is critical to determine what portion of that environment within the performance capabilities of the motion system is important to the pilot's control task.

The performance characteristics of the ASUPT motion base are summarized in table 1.

Table 1. MOTION BASE PERFORMANCE CHARACTERISTICS

Axis	Excursion	Acceleration
Forward - X	+49 in., -48 in.	±0.6 g
Lateral - Y	±48 in.	±0.6 g
Heave - Z	+39 in., -30 in.	±0.8 g
Pitch - Y	$+30^{\circ}$, -20°	$\pm 50^{\circ}/sec^2$
Yaw - Z	$\pm 32^{\circ}$	$\pm 50^{\circ}/sec^2$
Roll - X	$\pm 22^{\circ}$	$\pm 50^{\circ}/sec^2$

Each ram has a maximum velocity capability of 19 in/sec. It should be noted that the development phase of the ASUPT program was directed primarily at the methods of driving a motion system with the above tabulated performance parameters rather than attempting to alter the motion hardware to increase its performance capabilities.

Very little precise quantitative knowledge exists concerning the role kinesthetic simulation plays in the pilot training process. This stems from at least three basic problems plaguing the kinesthetic transfer of training question:

a. Problems in adequately defining performance measure.

b. The subjective nature of motion stimulation and the resultant wide latitude of opinion found within the population of subjects exposed to a given motion experience, and

c. The resultant uncorrelated sensitization or desensitization to various aspects of motion stimulation arising from the above mentioned opinion.

Much of the kinesthetic experimentation yielding relatively firm data points are laboratory type experiments wherein single task objectives are employed outside the spectrum of stimuli normally available to an aircraft pilot. The applicability of this data becomes suspect when attempting to reinsert it into the normal spectrum of stimuli and a multi-task loading environment in which a pilot operates.

One of the objectives of the ASUPT facility is to employ a motion system drive program which is easily altered by experimenter control for the purposes of investigating kinesthetic transfer of training in an applicable environment in terms of spectrum of stimuli and task loading.

MOTION DRIVE CONCEPTS

Nearly all motion simulation concepts begin with the obvious admission that the complete aircraft acceleration profiles cannot be simulated in magnitude and duration. A generally accepted hypothesis has been that the onset and leading edge of the acceleration profile contains the most significant kinesthetic information employed in tracking and control tasks. The ASUPT motion drive scheme is no exception in this respect.

First let us consider what we mean by an acceleration profile and the accelerations which are of interest. The accelerations which are to be simulated are those which exist at the pilot's position and are the product of the translational and rotational accelerations acting at the aircraft's CG transferred to the pilot's position (see figure 2) wherein they are experienced by the pilot.

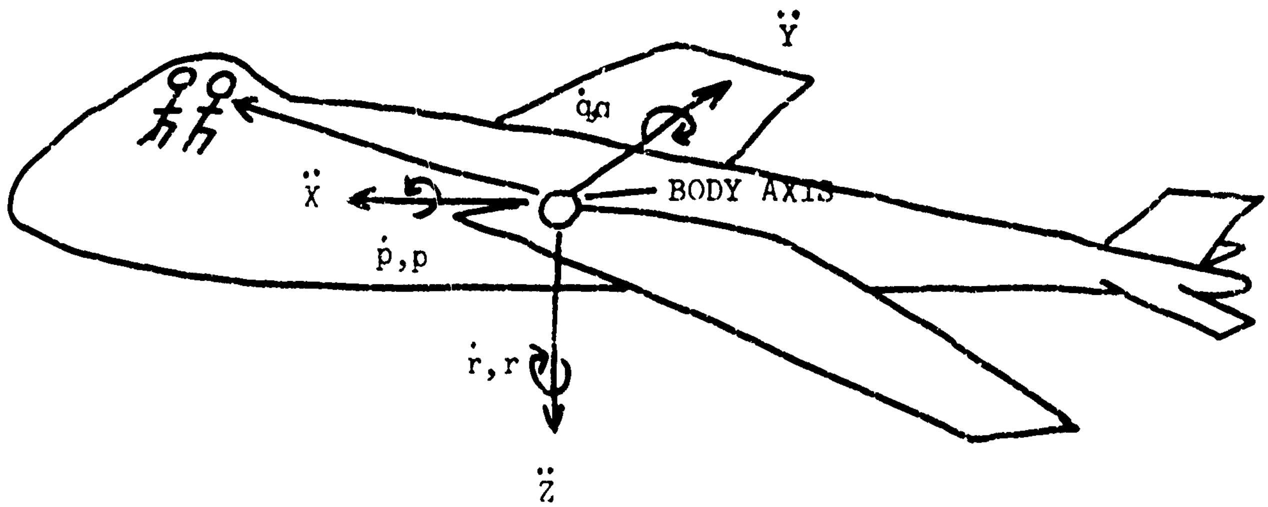


Figure 2. PILOT POSITION ACCELERATIONS

Inserting the motion system and the vector of transfer as above and noting that the cockpit plane of symmetry contains the axis of motion system roll (see figure 3), it becomes ap-

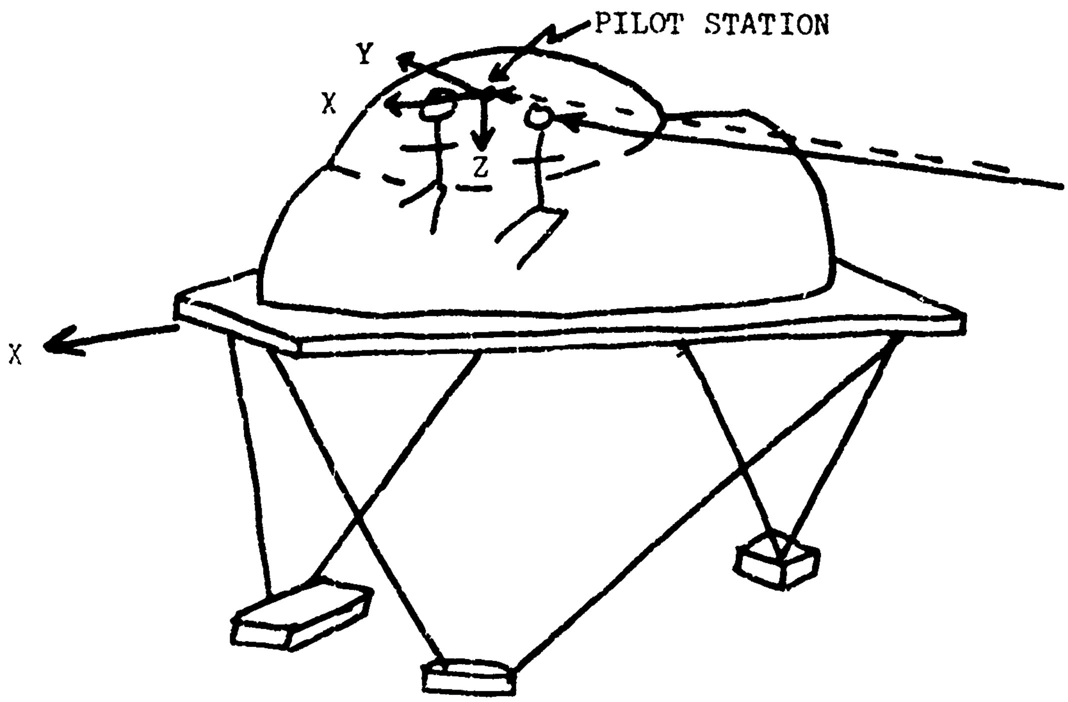


Figure 3. PILOT STATION FLIGHT DECK POSITION

parent that it is necessary only to transfer the simulated aircraft body axis accelerations (about the CG) to the plane of symmetry midway between pilot and copilot (dotted vector). The geometry of the motion system and the simulated cockpit will provide appropriate motion sensation to both pilot and copilot based on appropriate motion delivered to the plane of symmetry.

Obviously the above mentioned transfer of simulated aircraft acceleration to the pilot station results in translational acceleration components "induced" by rotation about the simulated aircraft CG similar to that which occurs in the actual aircraft. These induced components are algebraically summed, during the transfer process, with the translational acceleration components extant at the aircraft CG. The pilot station axis depicted above is constructed parallel to the body axis system.

Henceforth, in discussing acceleration profiles, it will be implied that we are discussing translational and rotational acceleration components in the pilot station axis system. An acceleration profile as used herein simply refers to these components in time history fashion.

TRANSLATIONAL ACCELERATION CONCEPTS

As mentioned earlier the onset phase of an acceleration profile is considered to be of primary interest. The primary vestibular sensing system is the utricle acting much like a linear accelerometer. The acceleration disturbs, by inertia effect, the location of the otoliths with respect to the macula. The hair-like sensors embedded in the macula and supporting the otolith register the inertial movement and provide the neural output. Haptic system pressure sensors also register changes in flesh pressure due to inertial body movement resulting from the acceleration profile.

Figure 4 illustrates the hypothesized response characteristics of the utricle and pressure sensors.

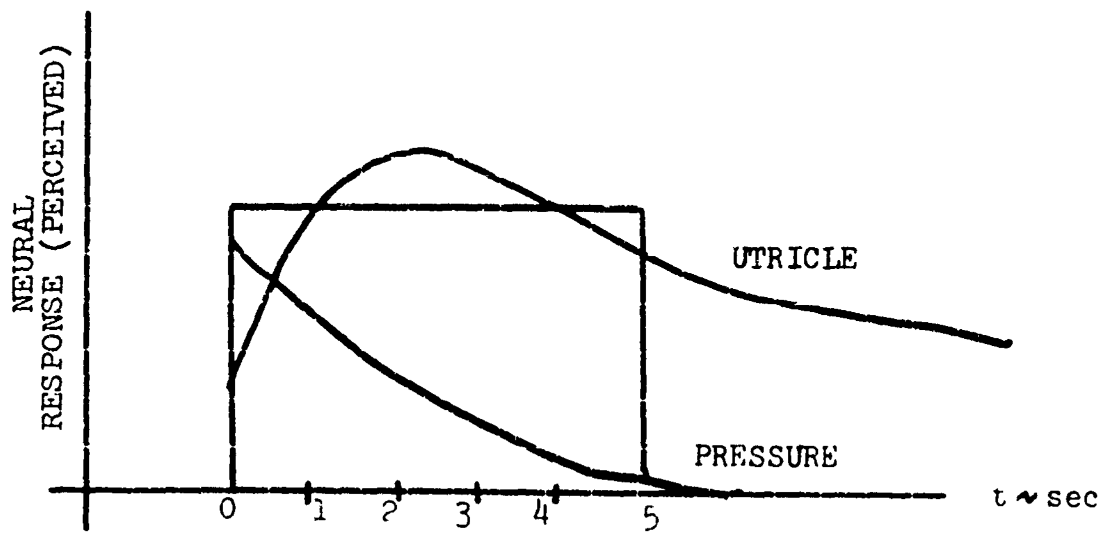


Figure 4. RESPONSE CHARACTERISTICS OF UTRICLE AND PRESSURE RECEPTORS

Both sensors display adaptation characteristics which lend themselves to the theory that the onset phase of the acceleration profile provides the significant neural output in response to an acceleration profile. The pressure receptors seem ideally suited to this concept due to the rapid rise time and rather quick decay. Unfortunately the utricle time dynamics are much longer and the onset phase argument weakens somewhat due to the fact that, as we shall see, performance characteristics of the motion system do not generally permit onset cue (acceleration simulation) duration extending into the significant phase of the utricle's adaptation.

The motion platform is normally positioned somewhere near the midpoint of its rotational and translational excursion envelope (a "neutral" point) for the nominal 1 G state such as that existing when the simulated aircraft is sitting on the runway or is flying straight and level unaccelerated flight. Such positioning permits bidirectional motion along/about each of the six degrees of freedom.

The display of an acceleration cue obviously results in some platform velocity and displacement from the neutral point. The duration of the acceleration cue is closely tied to the maximum velocity capabilities of the motion system. When maximum velocity is attained, acceleration becomes zero. Now the accumulated velocity must be returned to zero prior to exceeding the excursion capabilities of the motion system. Lastly it would be advisable to return the platform to the neutral point in preparation to display another onset acceleration phase cue.

Superimposing the above type of platform acceleration conditions on a simulated aircraft acceleration profile would produce the profile shown in figure 5.

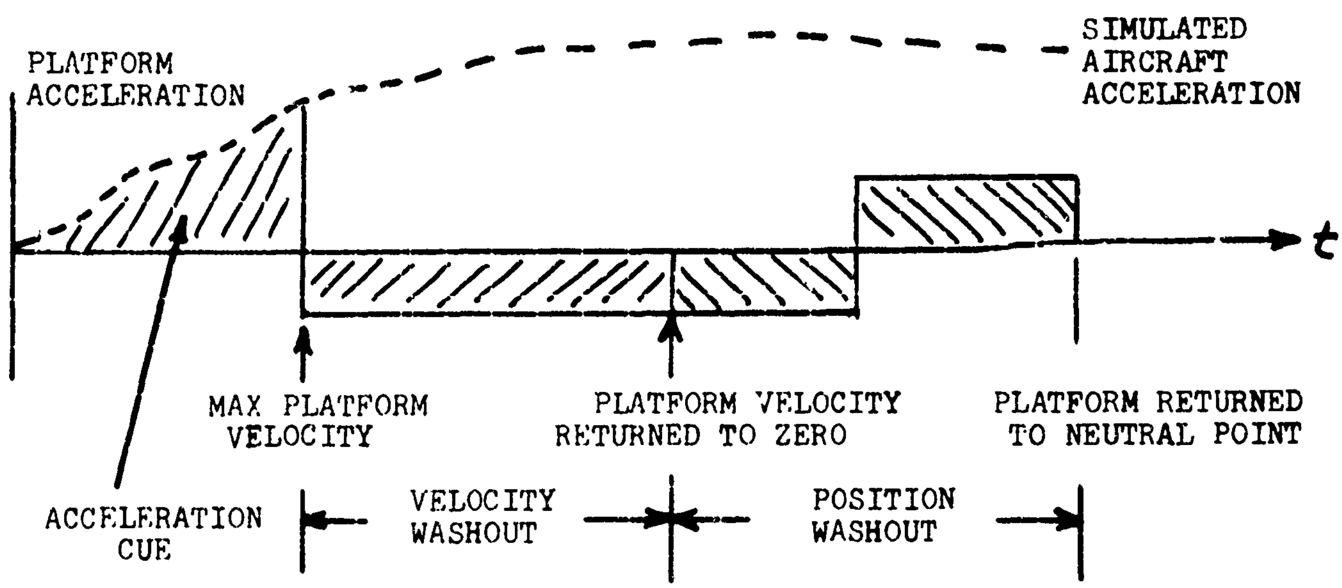
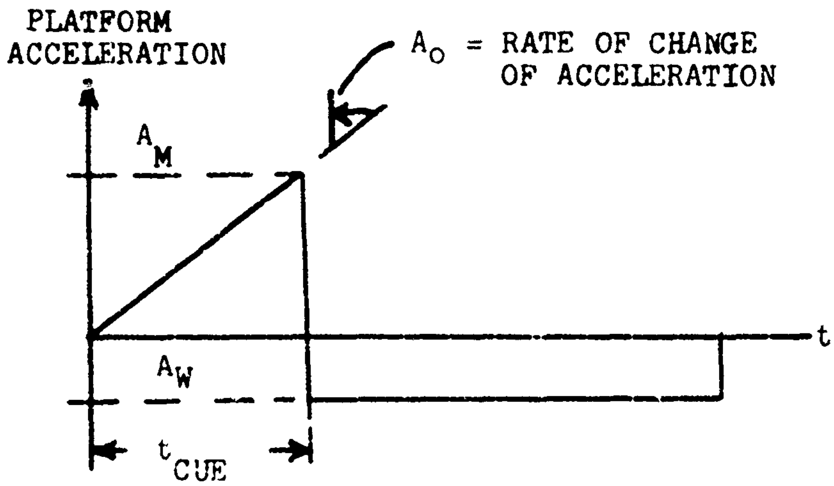


Figure 5. TRANSLATIONAL ACCELERATION & WASHOUT PROFILE

As denoted in figure 5, the period when platform velocity resulting from the display of an acceleration cue is returned to zero is called "velocity washout". Likewise the period when the platform is returned to the excursion neutral point is called position washout. The acceleration levels used in both of these washouts are designed to be very low level accelerations, subliminal in nature and not perceived by the pilot.

Now to provide an illustration of the duration of acceleration cues available, consider the profile in figure 6 as redrawn from figure 5.



Further let

V_L = maximum platform velocity

S_M = maximum platform excursion

Figure 6. SIMPLIFIED TRANSLATIONAL CUE PROFILE

The three plots shown in figures 7, 8, and 9 refer to this profile and provide a relationship between the above parameters. Each plot refers to a specific washout acceleration level, A_W.

Remembering that the ASUPT motion system maximum ram velocity is approximately 19 in/sec which, due to the mechanical advantage available through effective ram geometric positioning during design, may be converted to a maximum platform velocity of approximately 24 in/sec, an operating bound is inserted as a dotted line on each one of these plots.

Of importance here is the recognition that, of necessity, the duration of possible cues, t_{cue}, is quite short and does

not extend into the adaptation range of the utricle. Two other points are of interest with respect to the above profile and can best be understood by referencing the preceding plots. Both points pertain to the slope of the onset acceleration cue, A_O. The ASUPT software is configured to permit limiting

A_O to some maximum value nominally set at 1.25 g/sec which permits at least t_{cue} = 0.3 seconds prior to reaching platform

velocity limits. Nominally, 0.3 seconds is the minimum duration desired for an onset cue.

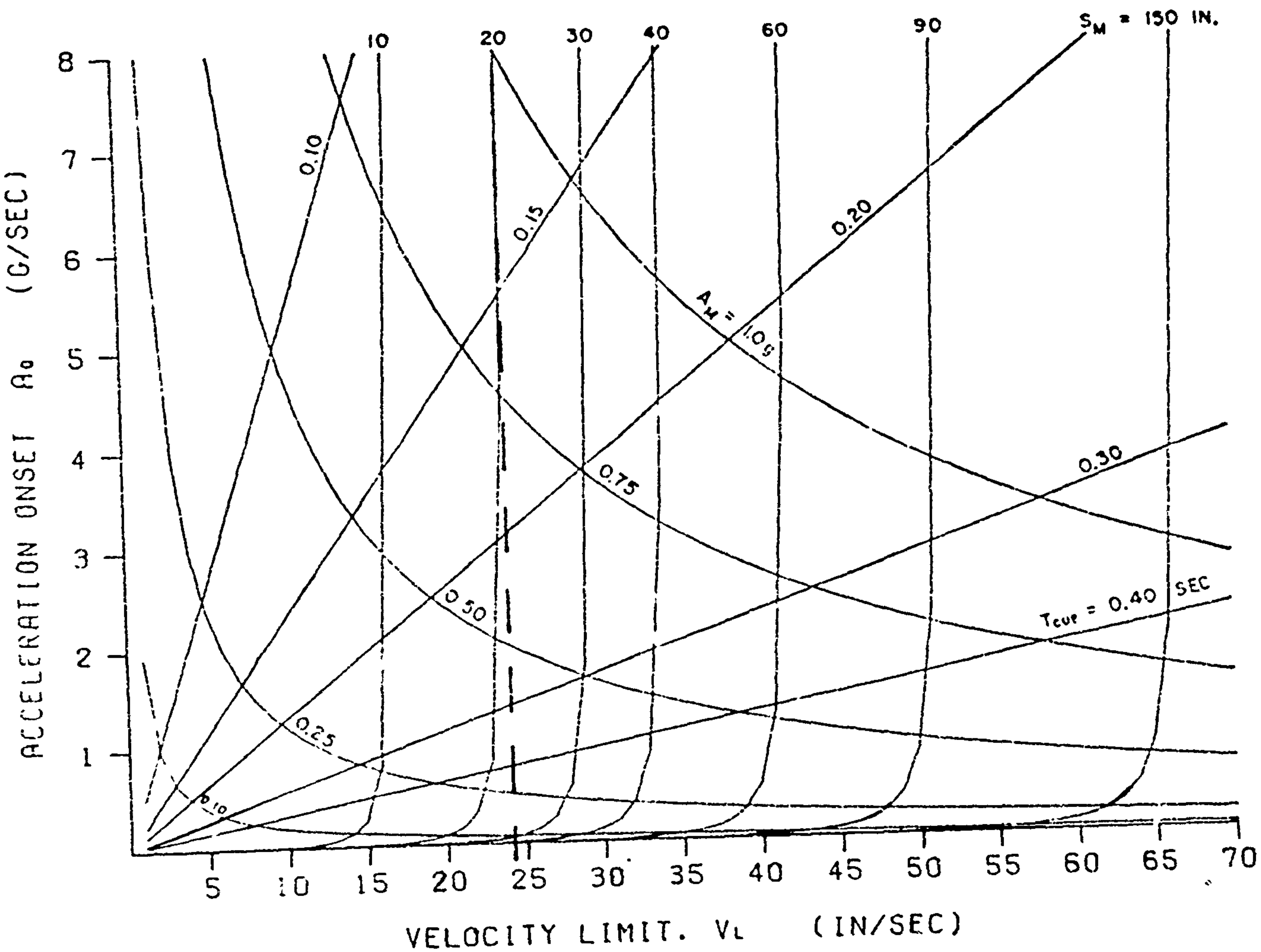


Figure 7. ACCELERATION ONSET VERSUS VELOCITY LIMIT, WASHCUT ACCELERATION, $A_W = -0.04g$

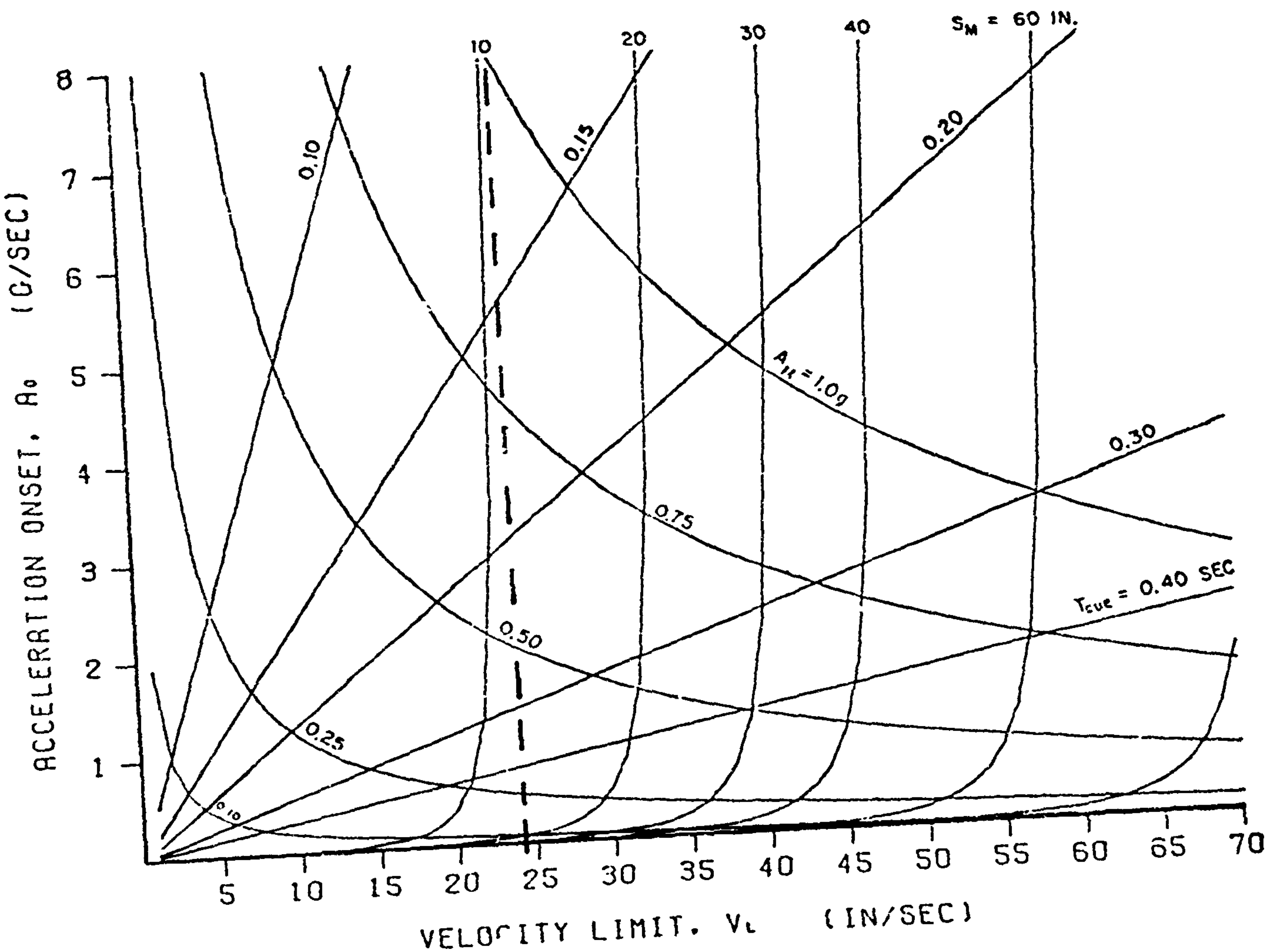


Figure 8. ACCELERATION ONSET VERSUS VELOCITY LIMIT, WASHOUT ACCELERATION, $A_W = -0.08g$

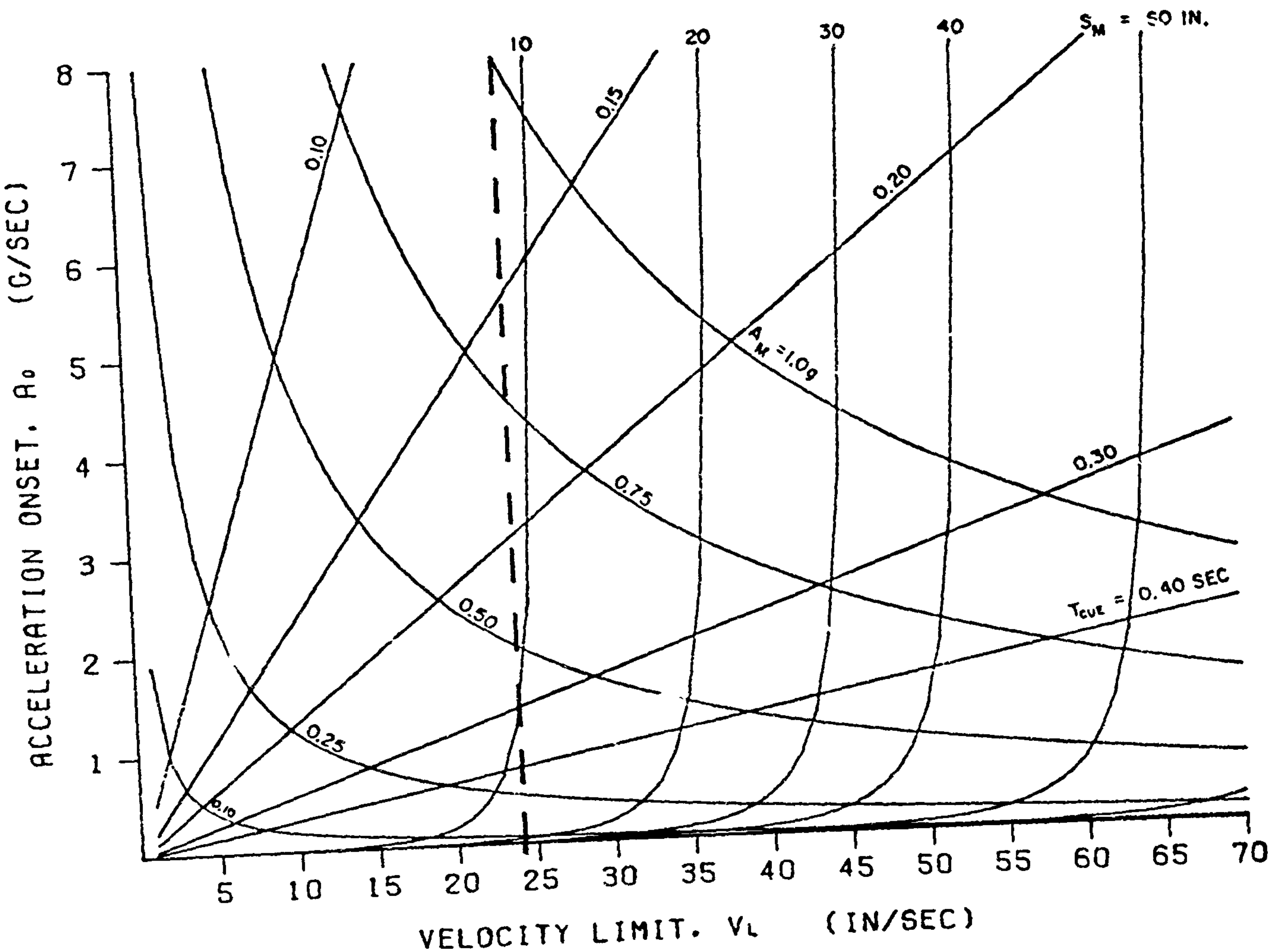


Figure 9. ACCELERATION ONSET VERSUS VELOCITY LIMIT, WASHOUT ACCELERATION, $A_W = -0.10g$

Secondly, the ASUPT software makes provision for limiting the minimum value of jerk, A_o. The nominal setting is 0.08 g/sec which is assumed to be the threshold of jerk. Acceleration profiles where A_o is less than 0.08 g/sec are considered subliminal and do not, therefore, qualify as desirable accelerations to simulate with platform acceleration. Display of such accelerations would cause the platform to drift about utilizing precious velocity and excursion capability without providing perceivable useful cues.

A typical ASUPT translational acceleration sequence differs slightly from those profiles presented heretofore. The most noticeable difference appears in the shape of the acceleration profiles used for velocity and position washout. A typical profile is presented in figure 10.

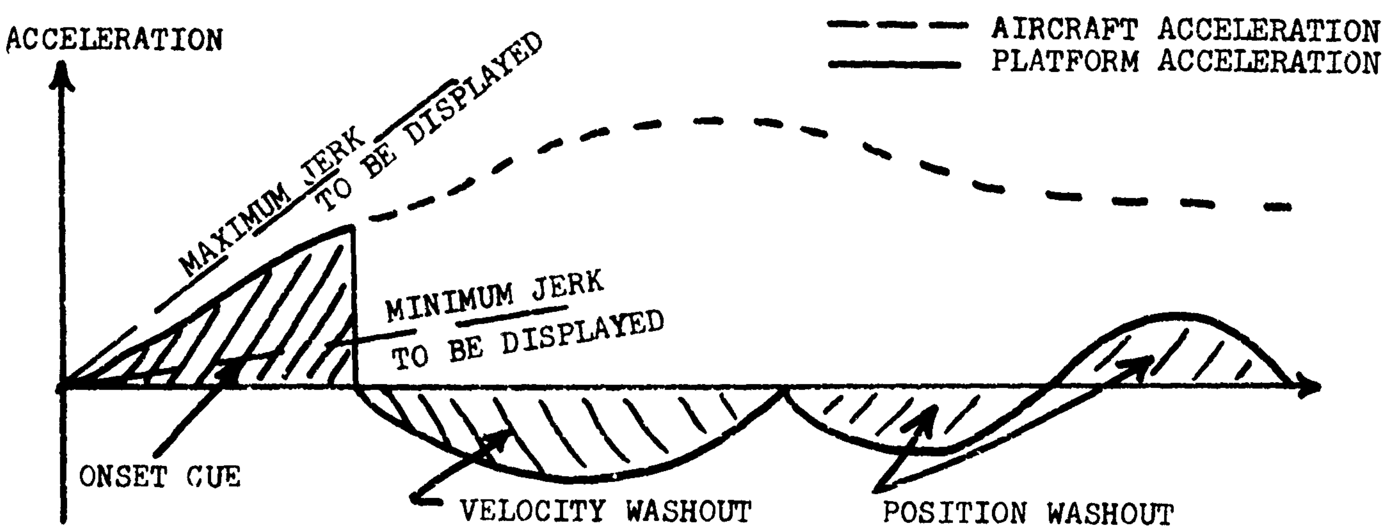


Figure 10. TYPICAL ASUPT TRANSLATIONAL ACCELERATION PROFILE

The ASUPT motion drive scheme is the only Simulation Products Division motion package configured such that platform acceleration during the onset cue phase exactly matches the aircraft acceleration in magnitude and shape. This will occur only if the aircraft acceleration profile remains within the maximum and minimum jerk levels set by the experimenter and further that the experimenter has not set the translational acceleration attenuator factors below 1.0 (no attenuation). Attenuation has been provided the experimenter for two reasons:

a. It has been observed during the design of other motion systems that an attenuated form of acceleration appears to be more realistic to pilots.

b. Attenuation of the onset acceleration increases possible onset acceleration duration prior to reaching maximum platform velocity.

Velocity and Position Washout

As alluded to earlier, washout refers to the practice of getting rid of something in a subtle unnoticed manner. The author is not certain of the origin of the term but hypothesizes a relationship between it and the term "washed out" as assigned to the fading of pictorial images. Velocity washout is the process of eliminating platform velocity built up during onset acceleration cue display.

Position washout is the process of returning the platform to the midpoint of its excursion sphere from wherever it was transported as a consequence of cue display plus velocity washout.

Both velocity and position washouts are designed to occur at acceleration levels which are subliminal to the pilot. Further, the rate of change of washout acceleration must also be subliminal and for this reason a half cycle sine wave and a full cycle sine wave are employed to generate velocity and position washout, respectively. The sine wave profile provides a very smooth rate of change of acceleration. The magnitude of washout acceleration is set to some value which may be inserted by the experimenter, individually, for velocity and position washout. The amount of acceleration required is, of course, established by the initial conditions upon entering the washout profiles (platform velocity upon commencing velocity washout, platform excursion from the neutral point upon entering position washout).

The amount of acceleration afforded by the washout profiles is controlled by determining the frequency of the above mentioned sine profiles which will provide just the proper acceleration to achieve the stated purpose: eliminate platform velocity, return the platform to the neutral point. Obviously the frequency of the profile determines the duration of the profile and herein lies an important design consideration. Because it is unlikely that any additional cues can be displayed until the conclusion of velocity and position washout (e.g., until system capability is regained) it is important to try to minimize the time spent in washout.

Consequently the washout acceleration level input by the experimentor is used even when the velocity to be washed out is less than the maximum system velocity or the position to be washed out is less than the maximum excursion capability of the system. This permits the period of the washout profiles to be shortened and consequently the duration of inability to display acceleration cues minimized.

Therefore it follows that as the experimenter lowers the maximum washout acceleration level he is also extending the period of time during which system capability is not regained and cues cannot be displayed. The converse is also true; however the experimenter must be careful not to raise the washout acceleration levels beyond the perception level extant under the current piloting task loading. In that these threshold levels as a function of the type of task loading associated with piloting an aircraft are not precisely known, ASUPT is designed to permit such investigation.

A half cycle sine wave is employed as the velocity washout profile simply from the standpoint that all that is desired is to eliminate the existing platform velocity and bring the platform to rest. A full cycle sine wave is required for position washout because at the start of position washout the platform begins at rest from somewhere out near its excursion bounds, is accelerated to move back toward the neutral point, then must be decelerated to come to rest at the neutral point. The resulting velocity profile is shaped like a half cycle sine wave and its maximum must not exceed the maximum system velocity. Therefore, an additional acceleration constraint is placed on position washout to prevent a failure to perform a complete washout due to encountering the maximum system velocity. This constraint materializes in the drive software as simply a maximum position washout acceleration limit computed as a function of maximum system velocity input by the experimenter. Thus the system is protected from an experimenter inputting too large a position washout acceleration level while in pursuit of minimizing position washout duration.

The velocity washout acceleration vector is directed to oppose the platform velocity vector existing at the commencement of velocity washout. The position washout acceleration vector is directed toward the neutral point. In both cases the vector is projected into the pilot station axis wherein the components are double integrated to position commands.

Cue Termination

Having the velocity and position washout profiles available is nice, however it is important to discuss the condition under which they are brought into play. As one might suspect from the proceeding discussion, cue display generates the conditions requiring a velocity washout, and cue display plus velocity washout generate the requirements for a position washout. A comprehensive rule is that cue display, velocity washout, and position washout are serial operations; if the first exists, the others will follow. It is sufficient to say that at the conclusion of velocity washout, position washout is required and in fact initiated as the last step of velocity washout completion.

But how is velocity washout initiated? The obvious answer is that when maximum system velocity is encountered during the display of an acceleration cue, acceleration will tend to zero and it is advisable to terminate the cue and enter velocity washout. This first reason, for there is yet another reason for cue termination, is a rather simplistic explanation and must be amplified.

System velocity constraints are represented by the maximum velocity the hydraulic rams are capable of achieving. During translational cue generation, the resultant desired platform position is geometrically converted to desired hydraulic ram position commands. The first past differences of these ram commands are used to determine ram velocity and monitored such that when any one ram broaches the maximum velocity conditions, the translational acceleration cue is terminated and velocity washout initiated. If cue termination were not effected, the ram broaching maximum velocity would enter a constant velocity zero acceleration condition and the remaining rams could continue to accelerate destroying the directional fidelity of the acceleration cue.

The second condition which can precipitate cue termination is ram excursion commands in excess of the permitted excursion limits. Now, it is not satisfactory to permit the acceleration cue to continue to be displayed until such time that ram excursion is exceeded for then there would be no excursion room necessary to permit a subliminal velocity washout; in fact, the platform would come to a rather abrupt halt under these conditions. Therefore, it is necessary, when considering total required excursion, to account for that excursion which will be required to permit total washout of the resulting velocity.

The tense of the above reveals that a predictor type operation is required. Simply described, the operation is effected in the following manner (refer to figure 11).

In the digital processing world the onset acceleration profile appears segmented and in step form.

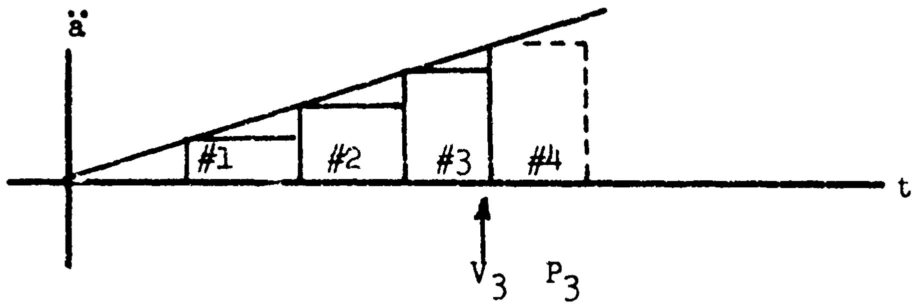


Figure 11. INCREMENTAL FORM OF PROFILE CONSTRUCTION

Assume we are considering the fourth frame of cue. We have already computed the velocity and position of the platform which exists at the conclusion of the third frame, V_3 and P_3, and, in fact, commands causing the platform to assume V_3 and P_3 have already been issued.

Before committing to display of the fourth's frame increment of onset acceleration it is considered first as a "trial" value and integrated once to velocity and once again to position, V_4 and P_4.

Now the velocity V_4 is used as the "potential" velocity to be washed out and the position required to complete such a washout computed and added to P_4 to form a final position after washout, which we will call $P4_{w/o}$. These computations are, of course, accomplished vectorially in the pilot station axis, and P_4 and $P4_{w/o}$ are geometrically converted to ram commands. The first differences of position using P_4 determine ram velocity and this is checked against maximum permitted ram velocity. The final ram position based on $P4_{w/o}$ is checked against maximum permitted ram excursion. Should either velocity or position be greater than the permitted values, the

fourth frame of acceleration cue is not accepted for display, the cue is therefore terminated, and velocity washout commences using V_3, as the velocity to be washed out. If, on the other hand, both of the above checks are within system capability, the fourth's frame of incremental acceleration will be accepted, the cue will extend through the fourth frame, and P_4 will be output to the rams.

Cue Onset

The discussion of cue termination was undertaken due to its interrelationship with velocity washout. Cue termination discussion should arouse some curiosity as to what qualifies for a cue onset. The reader will recall that we have already discussed that a simulated aircraft acceleration profile must display a rate of change exceeding that input by the experimenter as the minimum jerk level or subliminal threshold value. Should this subliminal value be exceeded as the acceleration profile (the total of the vectorial components) moves positively or negatively away from the zero (nominal 1 G) point, an onset condition exists. Likewise should this profile change sign an onset condition exists. A third case in which an onset condition exists is found when a supraliminal acceleration profile makes a radical change in direction as evidenced by monitoring the rate of change of the individual components of the acceleration vector. The fact that these three conditions produce an onset possibility does not guarantee that a cue will be displayed - the cue will occur under these conditions only if system capability exists. That is velocity and position washout must be completed and the system is therefore "cocked" and awaiting the onset condition.

Oscillatory acceleration profiles are commonly found in aircraft motion. The reader may have noted that the serial combination of onset cue acceleration plus washout acceleration represents a form of oscillatory motion and might wonder whether the motion system could capitalize on oscillatory accelerations generated by the flight software.

The motion drive scheme recognizes the value of oscillatory motion and makes provision for this under the concept of "reverse cues".

Reverse Cue

The obvious benefit of oscillatory motion as viewed by the ASUPT motion system designer is that the number of cues and consequently the percentage of total time devoted to cues may be increased significantly if an oscillatory acceleration profile can be used to supplant the washout process. That is, if a positively increasing acceleration profile is displayed as an onset cue and is followed very shortly after cue termination by a negatively increasing flight acceleration profile, it might be possible to display a supraliminal cue for this negatively increasing acceleration profile rather than remain in a subliminal washout process.

To provide this capability we change the aforementioned ground rules for onset conditions slightly and propose that the conditions for cue termination remain the same. However, once into the velocity and position washout process, the magnitude and direction of the washout acceleration profile will be compared to the magnitude and direction of the simulated aircraft flight acceleration profile and should the latter exceed the former in the desired direction, the flight acceleration will be accepted for cue display thereby achieving the washout and additional time devoted to cueing.

The reader will remember that position washout is designed such that maximum system velocity is achieved halfway through the position washout. During reverse cue consideration while in position washout a check of the rate of change of the reverse cue is effected to ensure that if the present rate of change is maintained during the next three frames (minimum desired cue duration) system velocity will not be exceeded. If the rate of change is large enough to cause such a violation three frames hence, the reverse cue is not accepted and the software continues to use the position washout acceleration profile as its means of returning the platform to the neutral point. This reverse cue acceptance constraint is additive, not in lieu of, the requirement that the reverse cue display a magnitude and direction sufficient to be used in place of the washout profiles. Figure 12 displays what a series of reverse cues might look like.

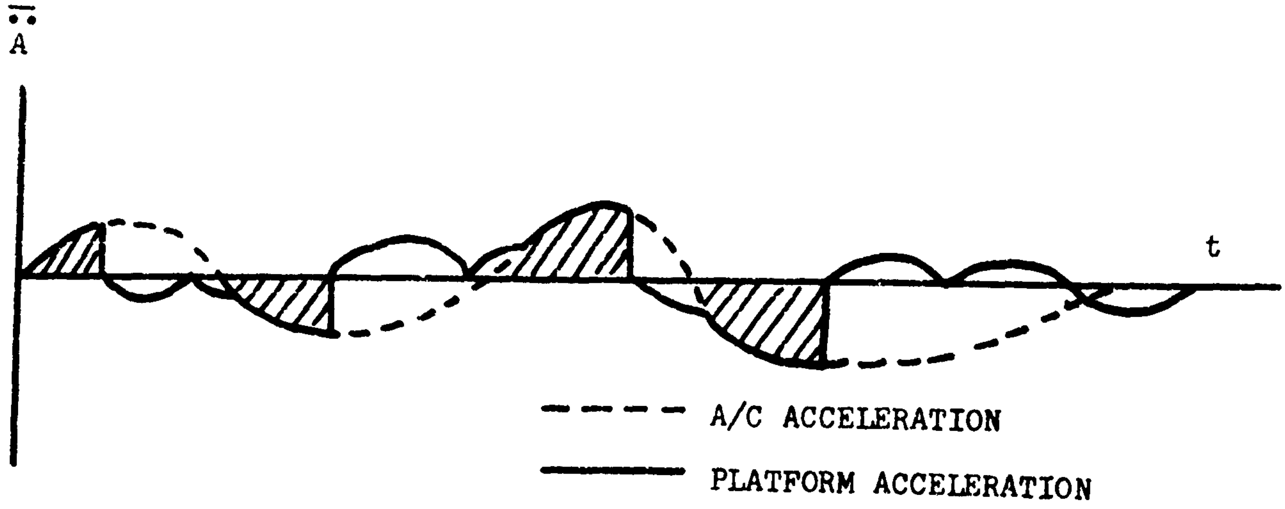


Figure 12. TYPICAL ASUPT TRANSLATIONAL PROFILES WITH REVERSE CUE

Other Washout Profiles

As previously stated the position washout profile is used to return the platform to the neutral point. Translational acceleration cues are normally terminated because of the maximum system velocity constraint - not due to lack of excursion. This is stated as a simple observation of the system in operation Most cues can be displayed with an expenditure of but a foot of excursion during the cue phase. With this in mind it is not terribly important to begin the cue precisely from the neutral point. Therefore it can be reasoned that it is not mandatory that position washout return the platform to, precisely, the neutral point. If the platform were repositioned to within an inch or two of the neutral point the probability is high that very little would be sacrificed from the next cue.

This lack of emphasis on the accuracy of position washout cannot be extended to velocity washout As one might expect, if the platform velocity is not totally washed out within the excursion allocated the washout, the end of a ram will be encountered and perceived by the pilot as a jerk. Velocity washout acceleration profile generation accuracy is therefore required.

Very significant inaccuracies could creep into the velocity washout if the acceleration profile cannot be digitally generated accurately. When the velocity to be washed out is small, the period of the washout acceleration profile is small. To reasonably generate the sinusoidal acceleration profile one data point per 60 degrees of period should be available. The execution rate is fixed so consequently a lower bound on velocity

to be washed out with the 1/2 sine wave profile is established. Velocities of lower magnitude than this limit should be washed out with another profile, more suitable to digital generation, if accuracy is a prime consideration. This secondary velocity washout acceleration profile is simply a square wave the magnitude of which is maintained at subliminal levels.

Most engineering tradeoffs as employed above to gain accuracy have a liability associated with them. The liability in using the square wave is the potential that the rate of change of velocity washout acceleration under the square wave may be supraliminal. We can only hope that since the velocities to be washed out with the square wave are small that the jerk level will not be perceptible to the pilot.

In summary, the platform translational acceleration can best be understood by examining figure 13, which depicts an example A/C acceleration and the platform response to that acceleration. The basic equations governing the washout profiles are provided as an aid to understanding the concept

SUSTAINED TRANSLATIONAL ACCELERATION CUES

It is readily apparent from the foregoing discussions that the physical limitations of most motion systems dictate very firm constraints concerning acceleration cue duration. As the term onset cue implies, the cue delivered is a very brief acceleration followed by the necessary washout. If for no other reason than environmental fidelity it would be nice to provide the illusion of an ongoing acceleration cue even after translational washout processes begin

The ASUPT G-seat[8] was developed as a sustained cue device. In practice it does seem to provide part of the illusion of sustained acceleration effects. Notably, it also seems to complement and enrich the onset cues available from the motion platform. The ASUPT motion drive scheme contains a subsection designed to provide its own form of sustained acceleration effects. This subsection is known as "gravity align" for, very simply, it attempts to make use of the gravity acceleration vector as a substitute for a portion of the external force vector operating on the simulated aircraft. At this point we truly enter the mystical world of attempting, through outright trickery, to fool the vestibular and haptic system physiological sensors.

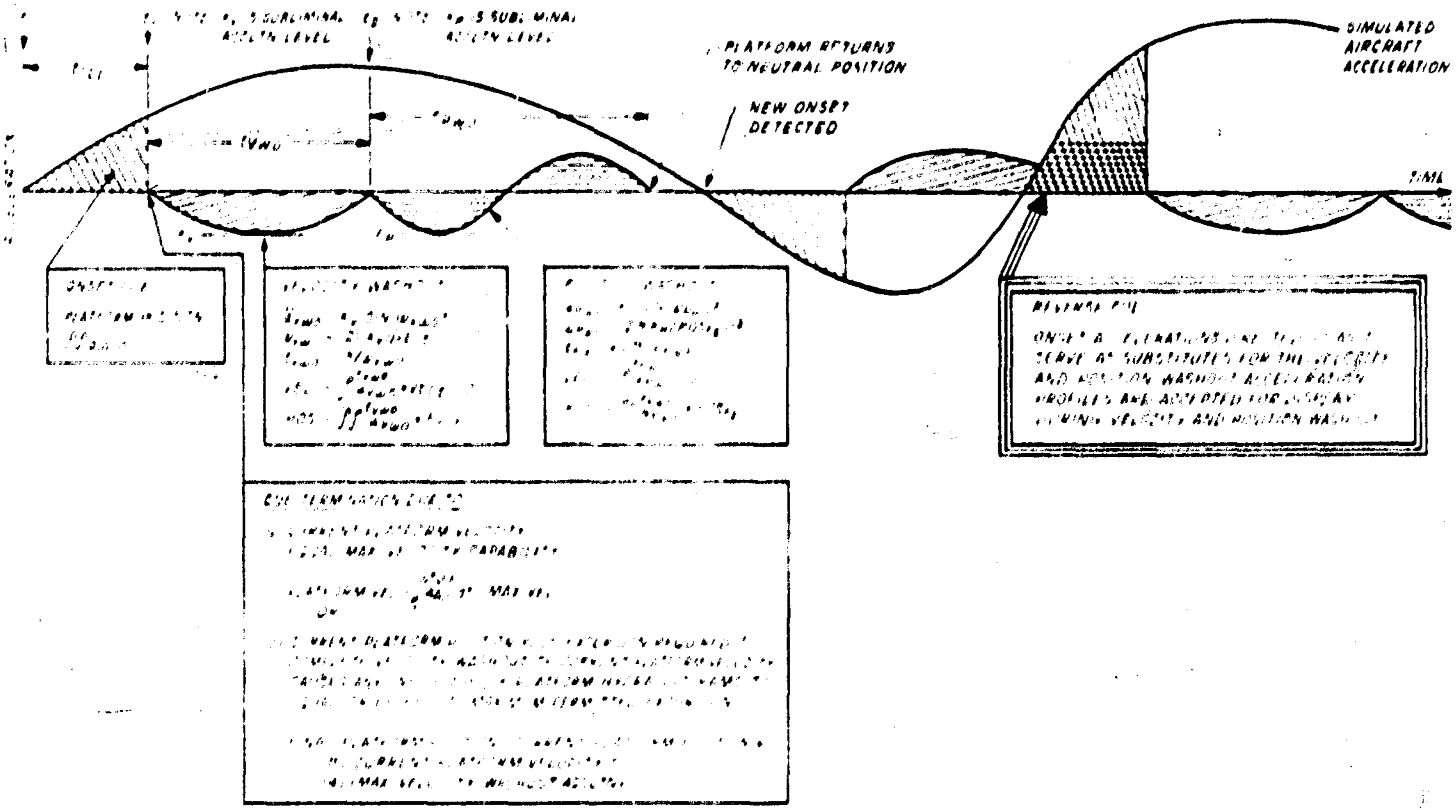


Figure 13. ASUPT TRANSLATIONAL MOTION SIMULATION

The next time the reader finds himself poised at the end of a runway in preparation for take off, he is advised to close his eyes during the first 10-15 seconds of take off roll after brake release. Upon opening his eyes, but before seeking attitude reference outside the aircraft, the reader should estimate the pitch attitude of the aircraft. Now look outside the aircraft for pitch attitude confirmation. Notice a discrepancy between estimated and actual pitch attitude? The author and a number of his collegues have noticed a tendency to believe that the aircraft is significantly pitched up well before takeoff rotation only to find such is not the case upon visual attitude confirmation against references outside the aircraft.

The author hypothesizes that the utricle is similarly affected when either the body is accelerated fore and aft or pitched up or down. Likewise the haptic system pressure receptors along the dorsal area of the body will similarly respond in either of the above motions. The author further hypothesizes that the semicircular canals are responsible for providing the information to the brain permitting it to discriminate between the two motions and correctly identify whether a translational acceleration or an attitude maneuver is responsible for the current utricle and pressure sensor sensation.

Upon brake release at the onset of take off roll, there are probably some very short duration supraliminal pitch cues followed by a gentle build up of translational acceleration. We know we are translationally accelerating but do not know by how much. We anticipate that the aircraft must pitch up to climb off the runway. Therefore, it would not be uncommon to expect some degree of pitch attitude confusion.

Gravity align design attempts to capitalize on the above interrelationship between attitude and translational acceleration but in the reverse direction. That is, attempting to stimulate the illusion of translational acceleration by motion platform attitude changes. Such attitudinal changes are designed to occur at rates subliminal to the semicircular canals such that the pilot is denied the discriminatory information required to establish that attitude is changing and is therefore, by default, led to believe that translational acceleration exists.

This concept is employed in both the longitudinal/pitch axis and also the lateral/roll axis. In essence the scheme calls for determining the vector orientation of the aircraft's external force vector

(acceleration) wherein the signs on ($\ddot{X}$, $\ddot{Y}$ and $\ddot{Z}$) A/C are negated. Having determined the orientation of this vector with respect to the pilot station axis (which rotates with the motion platform) the platform and consequently the inertial orientation of the above vector is subliminally rotated so that this vector is directed downward and aligned with the gravity vector. Figure 14 should help clarify this motion.

As is apparent from figure 14, the sustained cue available from gravity align is of necessity relatively small. Only a portion of the platform's attitude excursion can be devoted to this concept (set by the experimenter) in order to maintain some attitude excursion dedicated to rotational acceleration simulation. This excursion constraint placed on gravity align by the experimenter precludes worrying about gravity align commanding ram excursions in excess of the ram design limits in the pursuit of sustained acceleration simulation. Therefore odd external force orientations such as pure lateral or longitudinal do not represent a problem for they simply cannot be met even though the platform will rotate, within the assigned gravity align limits, in the direction providing a low level sustained cue representative of such aircraft accelerations.

Of paramount importance within the gravity align design is the absolute necessity to cause platform rotation to occur at levels subliminal to the semicircular canals. When first implemented experimentally by SPD in 1968, the development did not contain adequate control over gravity align rotational acceleration and velocity and consequently the ensuing rotational cues thoroughly confused the pilots and the scheme was abandoned.

Conversely, the ASUPT implementation provides very good rotational control at the experimentor's finger tips. During the latter phases of ASUPT HSI the author set

these limits at 0.12 deg/sec^2 and 1.5 deg/sec which, based on nominal T37 piloting task load, appeared to be very close to the subliminal level.

The foregoing illustrations demonstrate the method by which the platform rotates in response to changes in the orientation of the total external force vector of the aircraft. Mathematically the gravity align subroutine uses a cross product to determine the rotational vector required to cause a vector normal to the platform to be aligned with the I-frame external force vector. This

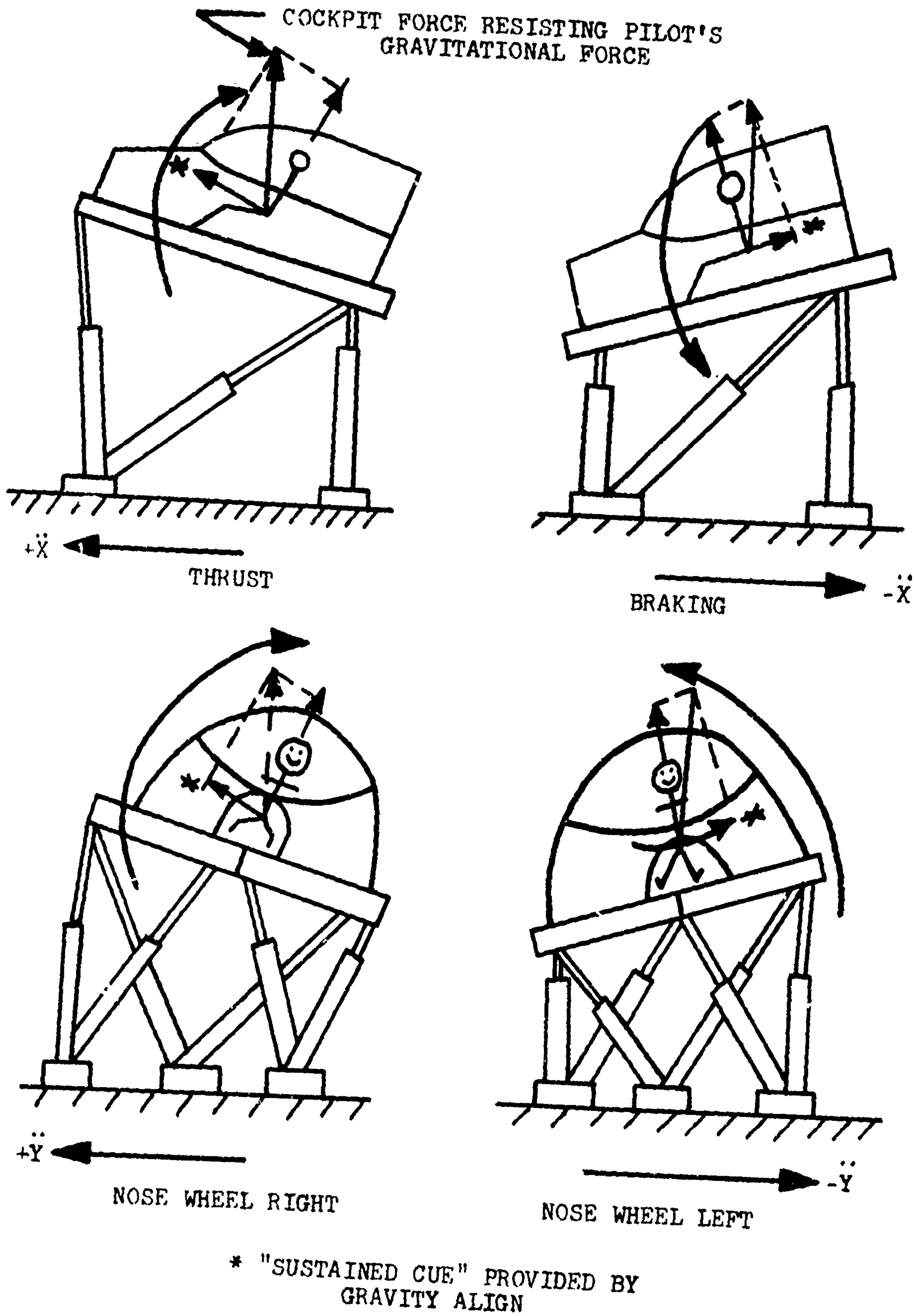


Figure 14. SUSTAINED ACCELERATION BY PLATFORM ROTATION

rotational vector is constrained to lie in the plane of the motion platform therefore producing only pitch and roll motion. The angular velocity of this rotational vector is limited to that value input by the experimenter and the desired acceleration, determined by the first past differences of velocity, is also limited to a maximum value input by the experimenter.

In computing the angular velocity required to achieve a desired platform attitude, the gravity align scheme recognizes the requirement that angular velocity must be zero at the time the desired attitude is met. To provide a predictive capability, the scheme uses an angular acceleration profile of simple construction figure 15.

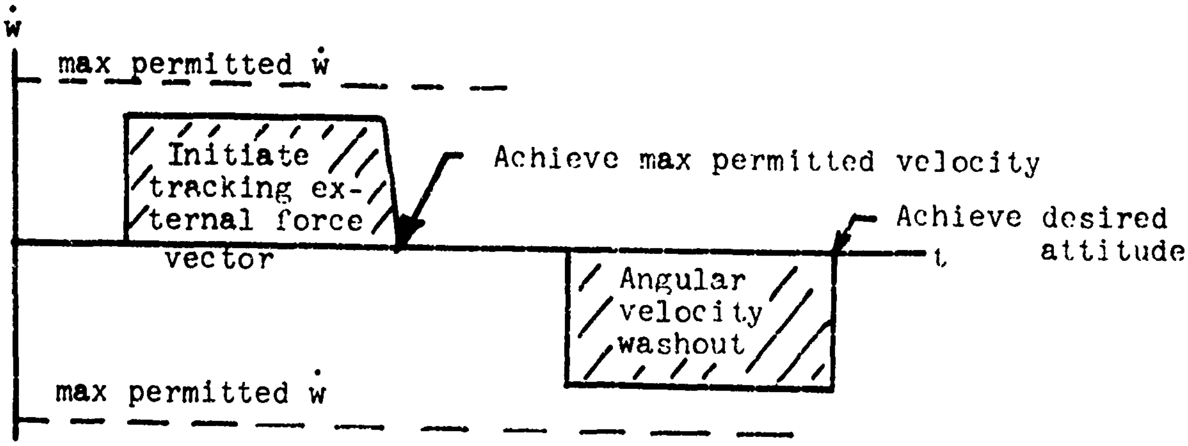
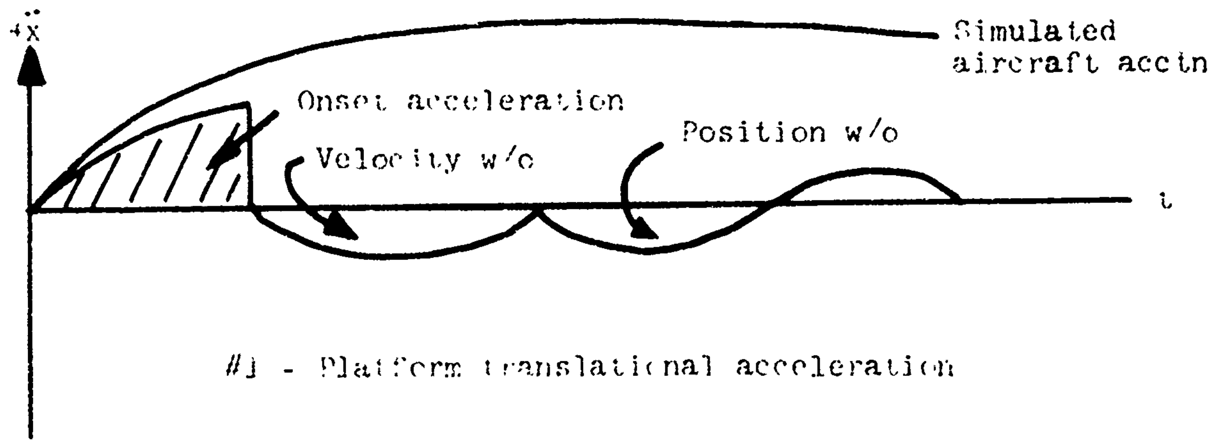


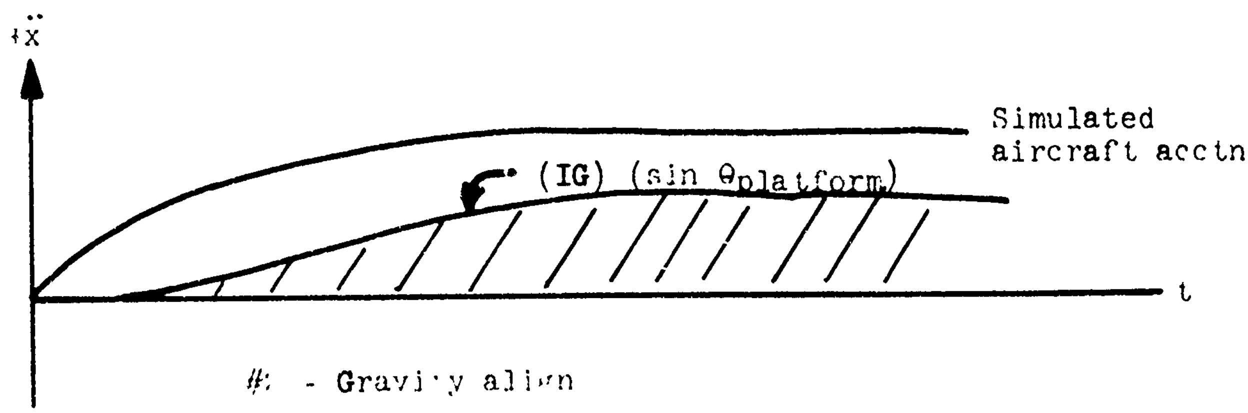
Figure 15. GRAVITY ALIGN ROTATIONAL ACCELERATION PROFILE

To eliminate any unnecessary platform attitude hunting a deadband is established and its size controlled by the experimenter. The deadband describes a minimum attitude change which must be broached by the orientation of the external force vector prior to initiating the above profile for tracking purposes.

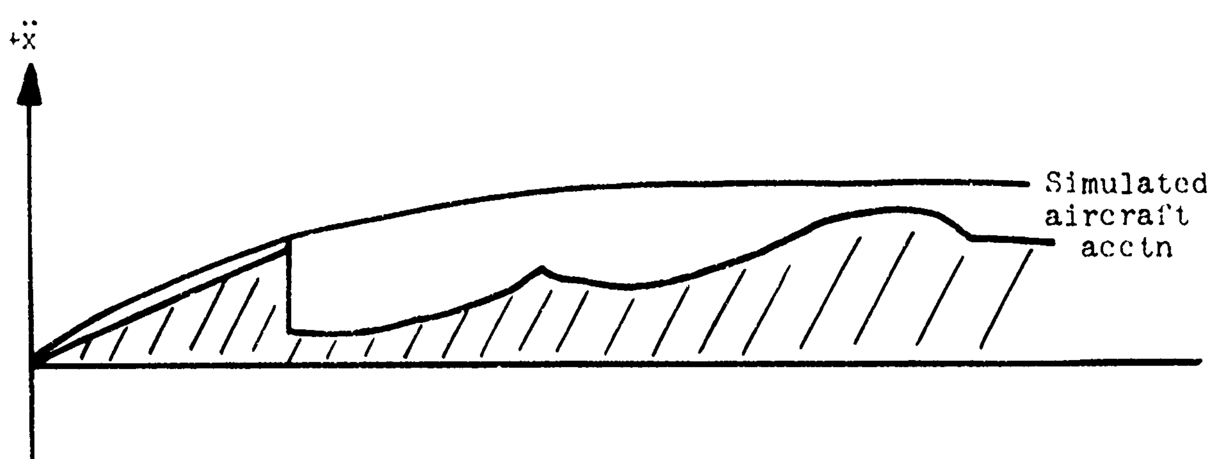
Figure 16 depicts in qualitative terms the role of gravity align in the process of developing translational acceleration cues. Note that the profiles available from platform translational acceleration (#1) and the gravity projection from gravity align (#2) are summed to provide the total translational cue (#3).



#1 - Platform translational acceleration



#2 - Gravity align



#3 - Total Acceleration Delivered to Pilot Trainee

Figure 16. ASUPT TRANSLATIONAL ACCELERATION PROFILE WITH GRAVITY ALIGN

ROTATIONAL CUE SIMULATION

Gravity align concepts are not the only source of platform attitude drive. To provide motion simulation in the six degrees of freedom it is necessary to provide a drive scheme for the simulation of pitch, roll and yaw rotational acceleration as well as the translational cue simulation.

It is the author's opinion that the ASUPT rotational acceleration scheme represents one of the more significant motion drive scheme developments. To understand this we must cover some preliminary ground. First the ASUPT translational acceleration cue scheme represents a significant departure from the standard motion drive scheme normally implemented by SPD.* The standard SPD cue scheme is known as the "transfer function" method and tends to provide valid jerk simulation. It does not provide the capability to attempt, even for short periods, to match platform acceleration in magnitude with that extant in the simulated aircraft; nor does it use analytically developed and executed washout profiles to regain system capability both of which were design goals in the ASUPT translational scheme. Rather, in its most simplistic form, the transfer function scheme accepts flight acceleration magnitude, scales it, passes it through a hardware representation of a second order filter and treats this output as platform position.

The analytic form of the translational washout requires that after cue presentation the platform is permitted to glide to the very end of the available ram length prior to commencing a position washout back toward the neutral point. There is no readily apparent penalty here because the pilot trainee does not have the reference information to determine whether he is one foot or three foot away from the translational neutral point. This is not the case, however, when considering whether a similar scheme should be developed for rotational acceleration simulation.

Should the platform pitch or roll to its rotational excursion bounds in order to wash out the rotational velocity built up during rotational acceleration cue display, the pilot trainee would be exposed to an attitude vastly different, and measurable through his assessment of platform tilt, than actual aircraft attitude. Only by chance would the two attitudes be anywhere near agreeing with one another. The washback, assuming it occurred at subliminal levels would be equally confusing for it might appear as a reduction of lateral or longitudinal force which had no business being there in the first place.

* SPD - Simulation Products Division (Singer, Binghamton, N.Y.)

With the above concerns in mind it appeared that although a departure from the standard method of generating translational cues was justified, such departure for rotational cues was not.

A secondary consideration was software expense in terms of time and core. The translational cue scheme and washout subroutines were developed first and found to be costly in terms of time and core. Constructing the rotational cue scheme in a like manner would double this expense; therefore, a less complex rotational drive scheme was desirable.

The SPD "transfer function" method of generating rotational cues is similar to that already described for the translational transfer function method except rotational velocity rather than acceleration is used as an input. This scheme is quite economical from a software position; but, more important, a platform rotational acceleration is delivered in the correct direction, and the platform attitude moves in the correct direction at reduced magnitudes from that found in the simulated aircraft. This holds true only to the point where the simulated aircraft rolls, for instance, more than 90° while executing an aileron roll. Obviously platform attitude can no longer represent, even at reduced magnitudes, the simulated aircraft attitude.

SPD's experience with the scheme has demonstrated that a large measure of importance in the aircraft control process seems to be attached to, at the very outset of control input, displaying the rotational acceleration smoothly in the correct direction and thereafter maintaining platform attitude magnitude near or below that of the simulated aircraft until such time the simulated aircraft's attitude, through ongoing rotation, enters regions well outside the platform's attitude envelope. In terms of an example, assume the simulated aircraft is flying straight and level and the pilot initiates a slow roll right trading off altitude/speed/direction such that the roll continues through 350° before he terminates the roll-left wing down 10°. An acceptable platform representation for this impossible-to-track maneuver is a slight roll acceleration right with gentle washout to a platform attitude of, say, 5°-10° roll right, a pause until the pilot chooses to stop the rotation and then a rotational acceleration left with gentle washout to platform level attitude.

The transfer function method of rotational cue generation was selected for inclusion within the ASUPT motion drive package. A very fundamental change was made in the manner of implementation, however, and herein lies the author's interpretation of a significant motion development. The classical transfer function scheme employs second order hardware shapers on each hydraulic ram between the linkage analog signal output and the hydraulic servo system positional input. This gives a characteristic acceleration response to a step positional input which appears as shown in figure 17.

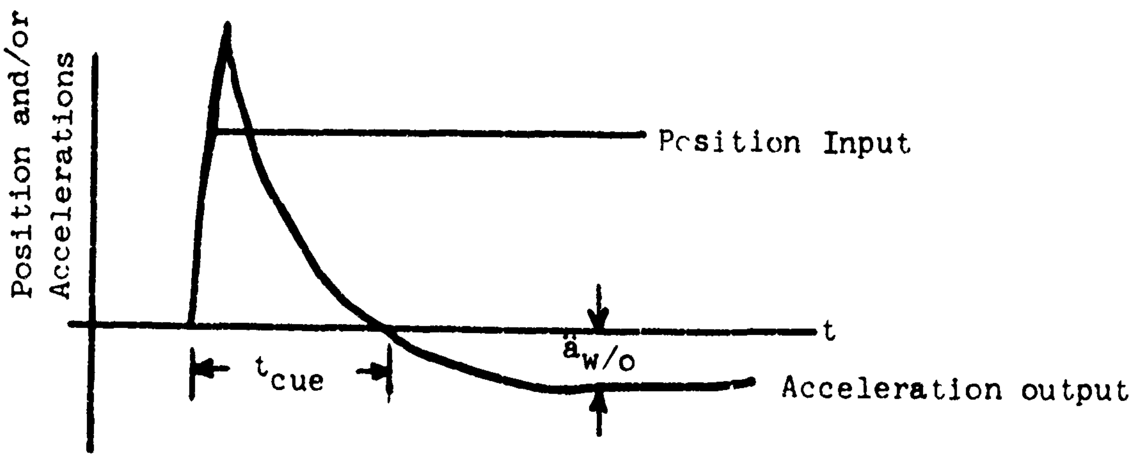


Figure 17. TYPICAL ACCELERATION OF SECOND ORDER FILTER RESPONSE TO STEP INPUT

This acceleration form has the desirable possibilities of superliminal onset and subliminal washout. By altering the poles (altering a and b) in the following LaPlace equivalent:

$$\frac{e_i}{e_o} = \frac{1}{(s + a)(s + b)}$$

t_{cue} and $\ddot{a}_{w/o}$ can be adjusted.

The classical transfer function scheme employed hardware poles set at approximately 0.5 Hz and 1.5 Hz (a and b, 3 and 9) which had been found, largely by empirical means, to provide relatively favorable acceleration cues as per pilot subjective comment.

The ASUPT design could not employ this hardware implementation because the 0.5 Hz bandpass could significantly affect the frequency content of the translational acceleration cue commands which must also pass to the hydraulic servo. To maintain the transfer function concept in the rotational cueing system it was necessary to remove the second order hardware shapers and cause their solution to be effected digitally prior to issuing ram positional commands to the linkage.

Now in their place was substituted 3.3 Hz active filters designed solely to trap the output rate stepping. The 3.3 Hz filters used with an output rate of 30/sec causes the hydraulic ram to, when commanded in acceleration, maintain said acceleration until commanded otherwise. The hydraulic servo loop is responsive enough that should an unfiltered step at 30/sec be issued the valve will open, acceleration commences then slumps to zero and finally enters deceleration as the commanded position is met by actual position and it is time to stop. This all occurs within the 1/30 sec time interval and could be interpreted as "platform stepping".

Secondly, in the interest of maintaining a responsive system and help preserve the conditions (clean, sharp steps) upon which the 3.3 Hz filters were designed, a lightly filtered D/A (natural frequency of approximately 320 Hz) was substituted for the more heavily filtered ($f_o \approx 7$ Hz) D/A's commonly used to pass ram positional commands to the motion platform hydraulic servos.

Now three important capabilities exist in the resultant design:

1. Translational cues and gravity align movement are not significantly further altered by the presence of a low pass shaper.

2. The shaping that is intended will occur on each rotational axis because the digital solution to the shaper will, by software design placement, be executed prior to geometric conversion to individual ram axial direction.

3. Perhaps most important and in keeping with the research design of ASUPT, the experimenter is provided a means, not available in the classical system short of attacking the hardware with a soldering iron, of altering the magnitude <u>and</u> <u>response</u> of the platform rotational cues.

Very briefly the following operations occur within the ASUPT rotational cue generation scheme:

Simulated aircraft rotational velocity p, q and r are input to the subroutine in a sequential three pass loop. The

reader might question the use of rotational velocities as an input rather than acceleration but is cautioned to remember that in the digital world of discretely stepping accelerations the first integral provides smoothing of a parameter which tends to be "spikey" and short term in nature. This is particularly important when the servo system waiting at the end of the command loop is as highly responsive as is the ASUPT motion system. Secondly the reader should recall from our brief discussion of the vestibular system that the apparatus we are attempting to stimulate, the semicircular canals, is sensitive not only to rotational accelerations but also rotational velocity. To this the author would like to add the observation that in cases where SPD has experimented with both rotational acceleration and rotational velocity as drive sources, pilots appear to select the latter as producing "more realistic" motion.

Continuing, the rotational velocity is scaled by a K factor gain term which essentially establishes that the full platform attitude excursion devoted to rotational cues, nominally ± 15 degrees, will be commanded only when maximum simulated aircraft rotational velocity is experienced. The gain term acts therefore as a transform device converting velocity magnitude to degrees of platform rotational excursion. Proper scaling ensures that, within the performance envelope of the simulated aircraft, platform attitudinal excursion exists for all rotational cues. The magnitude of the gain term obviously affects the magnitude of the resulting platform rotational accelerations and velocities and as such are available to the experimenter.

The rotational velocity as modified by the gain term is treated as a "positional" input to the difference equations which represent the solution to the second order shaper. The poles of this shaper are available to the experimenter however only one shaper is used for all three rotational axes consequently altering the response of the shaper for one axis must be weighed against the resultant effect in the other two axes.

The resultant attitudinal output from the shaper is summed with gravity align demands made on the axis in question and converted geometrically to a required ram positional command.

Figure 17, which describes shaper acceleration output in response to a step input, is not very representative due to the fact that although the digital world "steps" along, the input to this shaper (rotational velocity) ought to be defined as a continuously varying signal. Figures 18 and 19 depict the results of an offline simulation of the salient features of the ASUPT rotational cue generation scheme. The input to this model is a "stick out and hold" maneuver and this input is delivered to a simplified set of flight equations containing T37 type aero characteristics.

CUE COMPOSITION

We have been discussing three motion drive scheme concepts: translational acceleration, gravity align, and rotational acceleration. Each one of these concepts makes demands upon system capability, namely hydraulic ram velocity and excursion. The demands are additive and consequently an excessive demand on any one ram does not mean that all three cue sources must be deactivated. A hierarchy of deactivation is established.

The first cue source to be terminated is the most greedy, in terms of required system capability, of the three - platform translational acceleration. However termination of this cue can be, in some cases, a two pass effort. If an excursion violation of any one ram is detected employing the "trial" value of additional cue acceleration, the cue is terminated forthwith. On the other hand, if the violation is a velocity violation a second pass is effected at the old value of the cue acceleration (N-1 frame) to determine if the velocity violation can be eliminated. If the velocity violation is so eliminated the cue is maintained at least one more frame. If the velocity violation is not eliminated cue termination is effected. This seemingly "never say die" process is indicative of the importance attached to extending the duration of translational acceleration cues.

Now, upon translational acceleration cue termination, a retest is effected with the ram demands made by the remaining two concepts as well as velocity or position washout which commences because of the translational acceleration cue termination. The reader will recall that specific attitudinal bounds are established for the display of rotational cues (nominally ± 15 degrees). These bounds are easily altered by the experimentor as are the bounds on gravity align attitude. It should be noted that the former establishes an overriding bound for both concepts out of which the latter must operate. As long as the experimenter does not establish bounds in excess of the stated platform excursion capabilities there is little danger of ram excursion violations stemming from either gravity align or

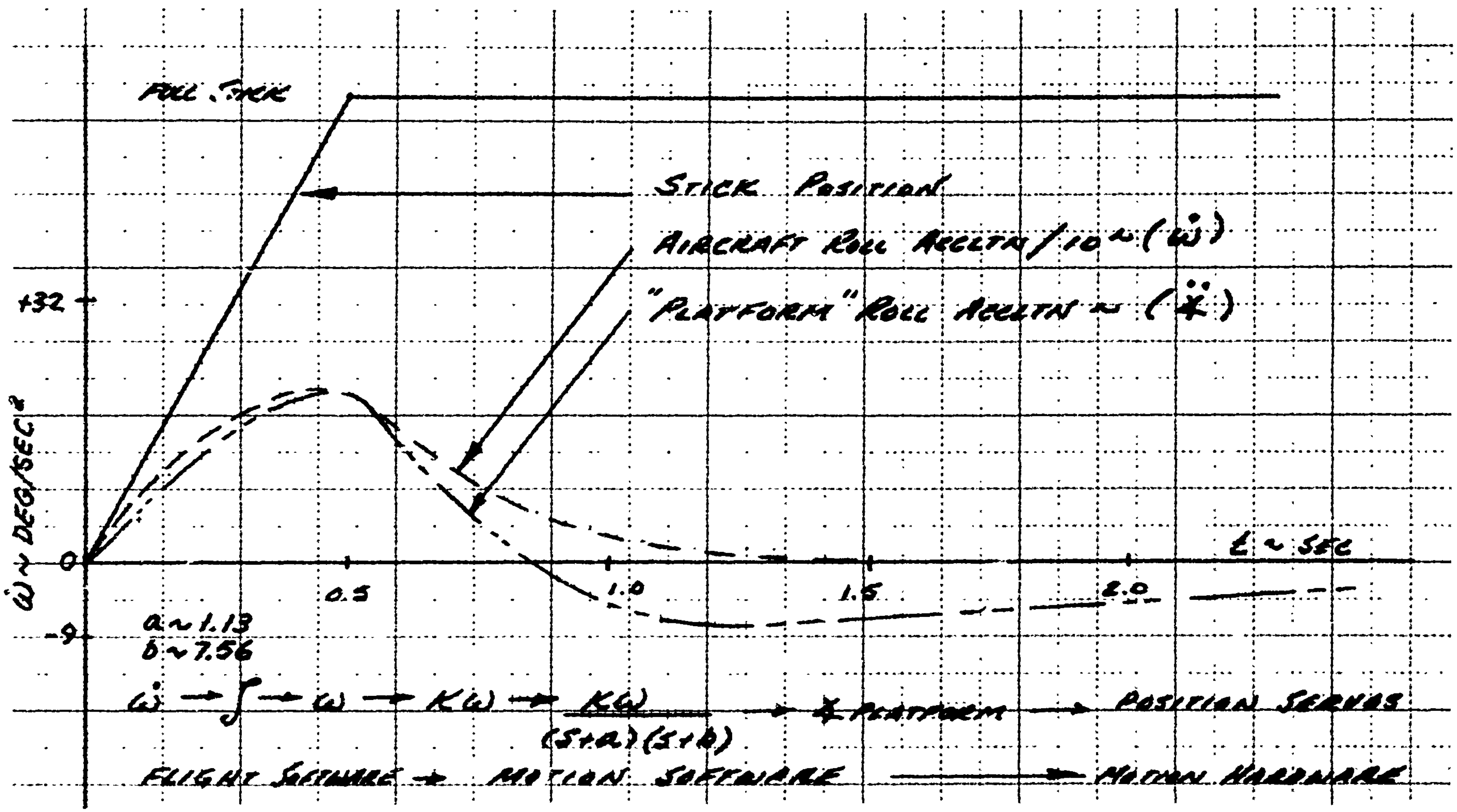


Figure 18. AIRCRAFT AND THEORETICAL PLATFORM ACCELERATION RESPONSE TO STICK INPUT

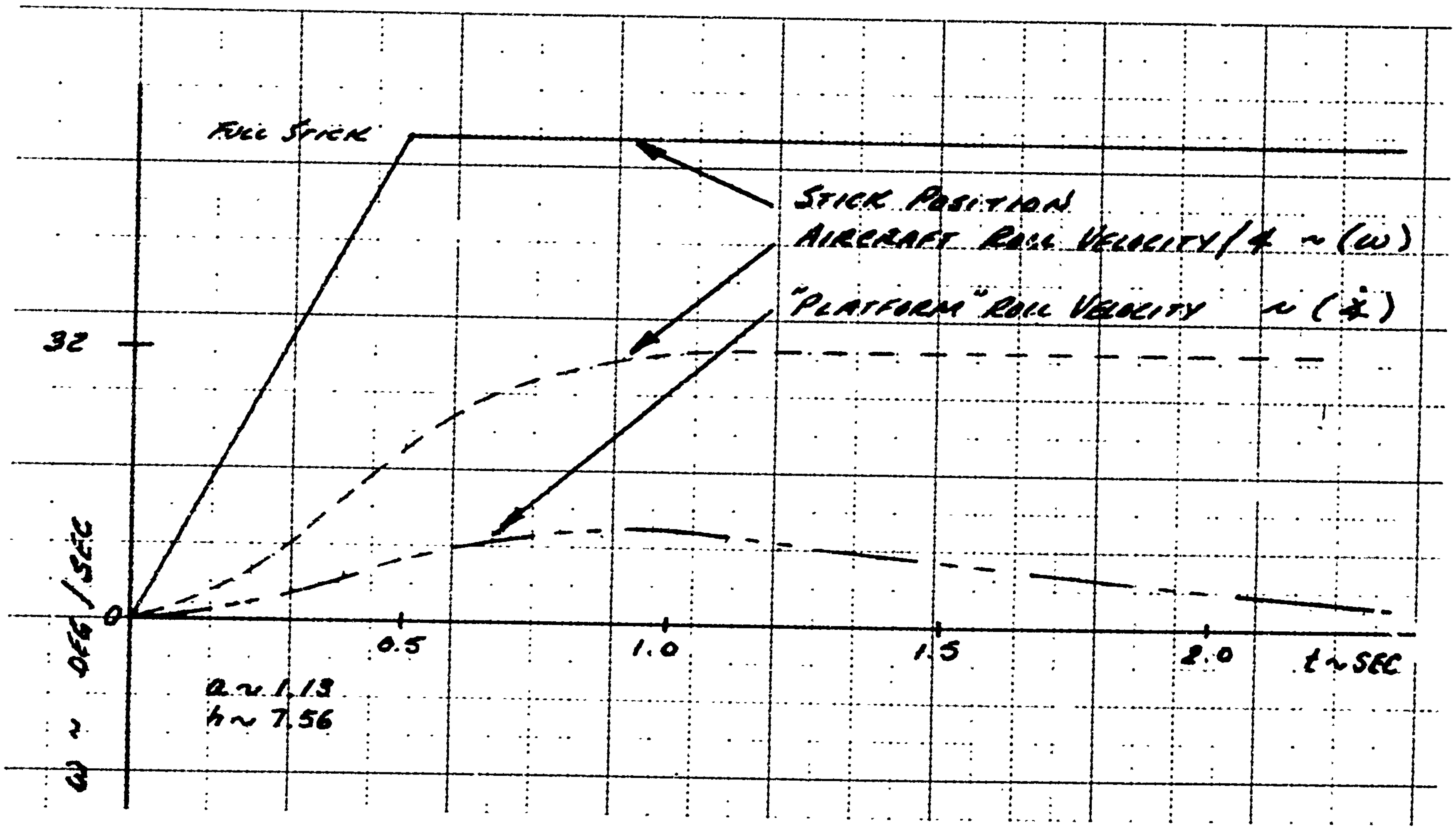


Figure 19. AIRCRAFT AND THEORETICAL PLATFORM VELOCITY RESPONSE TO STICK INPUT

rotational cues save for the problem that the translational cue may have carried the platform to a position where simultaneously gravity align and rotational cue attitude excursions cannot be met. For this reason the experimenter must judiciously set his maximum attitude bounds; for this reason also it may be necessary to terminate cues from one or both of the gravity align and rotational cue schemes.

Although gravity align does not make large system velocity demands due to the subliminal nature of its rotations and therefore does not represent a significant "savings" upon elimination in the hierarchy of rejection, it is the next to go. It is summarily dispensed with, in one pass. It should be noted that even before gravity align is thusly terminated, rotational cue generation is given priority in attitudinal demands. That is to say if rotational cueing required a portion of the envelope assigned to gravity align, it takes it and what's left over belongs to gravity align. It is the author's assumption that the designer elevated rotational cueing above gravity align in both excursion demands and termination sequence due to the belief, which seems quite logical, that rotational cues are of greater importance to the control task than is the sustained translational cues produced by gravity align. We have already noted that translational acceleration is first to go because of its large demands on system capability.

Continuing, if ram velocity and excursion violations continue to persist with both translational and gravity align cues terminated, rotational cueing is terminated leaving just washout operating to regain system capability.

MOTION SPECIAL EFFECTS

The primary low frequency translational and rotational acceleration cues are not the only motion cues of meaning to a pilot. Higher frequency vibrations or rumble as well as single shot "jolts" have an important role in improving environmental fidelity within the simulation and, of discrete operations such as the thump experienced as tires meet the runway upon landing. Vibrations can also provide an input to continuous control system tasks as evidenced by the high performance fighter aircraft pilot who mentally establishes his angle of attack by perceiving the amplitude and frequency of the cockpit/seat vibrations.

The first premise which must be accepted in discussing the special effects package is that, in vibration/rumble and discrete jolt conditions, the primary meaningful inputs are frequency and amplitude. Shape and duration of each vibratory or jolt pulse are not subject to discriminatory analysis. This tends to be borne out by noting that the hypothesized response characteristics of the semicircular canals and utricle commences a significant roll off at 1 Hz

or below. The primary mechanisms for experiencing vibratory information are more than likely elements of the haptic system such as the pressure receptors. The author hypothesizes that due to the "burst-fire and adapt" nature thought to exist for pressure receptor neural response, frequency and amplitude may be subject to discrimination but shape and duration likely are not.

With this in mind the motion system designer may approach the problem of generating vibration with a random number generator which in its highest frequency condition would output alternate signed ram commands on successive computational frames. This then establishes the maximum frequency obtainable at $\frac{1}{2}$ the iteration rate in cycles per second. In the case of ASUPT, the special effects package is processed at 7.5 iterations per second permitting a frequency of 3.25 Hz to be output to the rams. The amplitude is governed by the size of the ram excursion command which is limited to ± 1.64 inches maximum. It should be noted that this vibration command, known commanly as "buffet", is output through its own D/A directly to the position input of each ram's servo loop. It bypasses the 3.3 Hz "stepping trap" discussed earlier.

The ASUPT special effects repertoire includes the following:

Discrete Bumps - gear down and locked bump
- runway touchdown bump

Constant Amplitude Rumble*
- gear in transit rumble
- gear down aero rumble

Variable Amplitude Rumble*
- speed brake - function of extension
- runway - function of on ground velocity

Other
- aircraft zero buffet

*random number generator effects employed

Some of the above deserve additional description. The aero buffet, for instance, is totally generated within the flight software and passed to the motion special effects package for inclusion in the expression which makes up the square wave buffet channel output. Runway rumble (figure 20) is generated by employing the product of a flight software random number generator and clipping the peaks as a function of "on ground velocity."

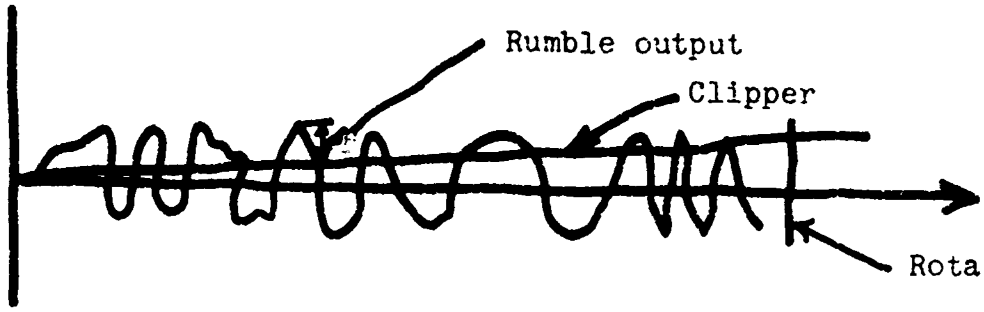


Figure 20. RUNWAY RUMBLE GENERATION

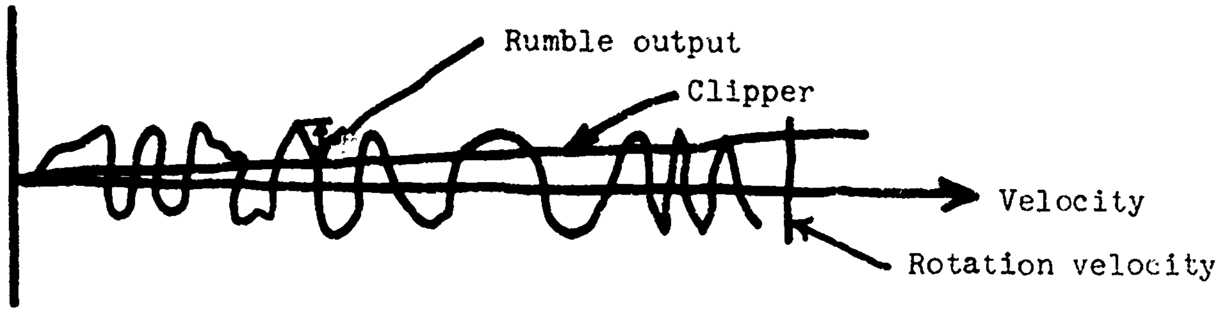
In this manner as lift builds up as a function of on ground velocity the effects of runway rumble become increasingly smaller and bleed to zero at rotation velocity.

It should be pointed out that rough air, sometimes mistakenly assumed to be a product of the motion special effects package, is produced wholly within the flight software and passed, via the simulated flight accelerations, to the motion software. Here they are reproduced within the primary translational and rotational acceleration cues.

ASUPT DRIVE SCHEME STRUCTURE

In this section we will introduce the manner in which the concepts previously discussed are mechanized to form an integrated motion system drive package. This introduction will be conducted on a rather general conceptual level. The reader is referred to the ASUPT Motion System Computer Programs Documentation, ASUPT-74.[5]

The drive signals the motion software are responsible for producing are simply the position, as a function of time, required of each ram. When the platform is not rotated and not translated from the neutral point the platform is positioned level and about 5 inches below the elevation which would result if all six rams were stationed at the midpoint of their excursion range. This is effected to optimize the platform excursion envelope in multi-axis simultaneous motion. This is the point from which all simulated motion begins and is the point to which the platform returns when in the nominal unaccelerated 1G simulated environment such as parked on the runway or straight and level flight.



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The reader should refer to the artist sketch of the platform at the beginning of this document and mentally position himself above the platform looking forward (out of the page) and down. He sees six rams and three bipod attach points identified as below. The base of each ram is fixed to the floor. The upper end of each ram can rotate about the floor joint in two degrees of freedom and extend and contract axially. To determine a desired ram length it is necessary to keep track of what we do with the free end of the ram. This, of course, can be accomplished for sets of ram pairs if we keep track of what we do with the bipod attach points and this is accomplished by defining the position of the bipod attach points in some fixed frame called an I frame (inertial frame) which, as long as it stays fixed, could be located at any convenient point in the vicinity of the platform. The movement of the bipod attach points (figure 21) will be a function of the vectorial sum of the movement caused by platform motion in the six degrees of freedom (figure 22). The motion in the six degrees of freedom is, in turn, caused by the implementation of the concepts we have already discussed. The point of this discourse is to demonstrate to the reader that there is nothing complex in generating ram length commands for a synergistic system and secondly, the importance of reducing our thinking to one of maintenance of bipod attach point position definition in the I frame.

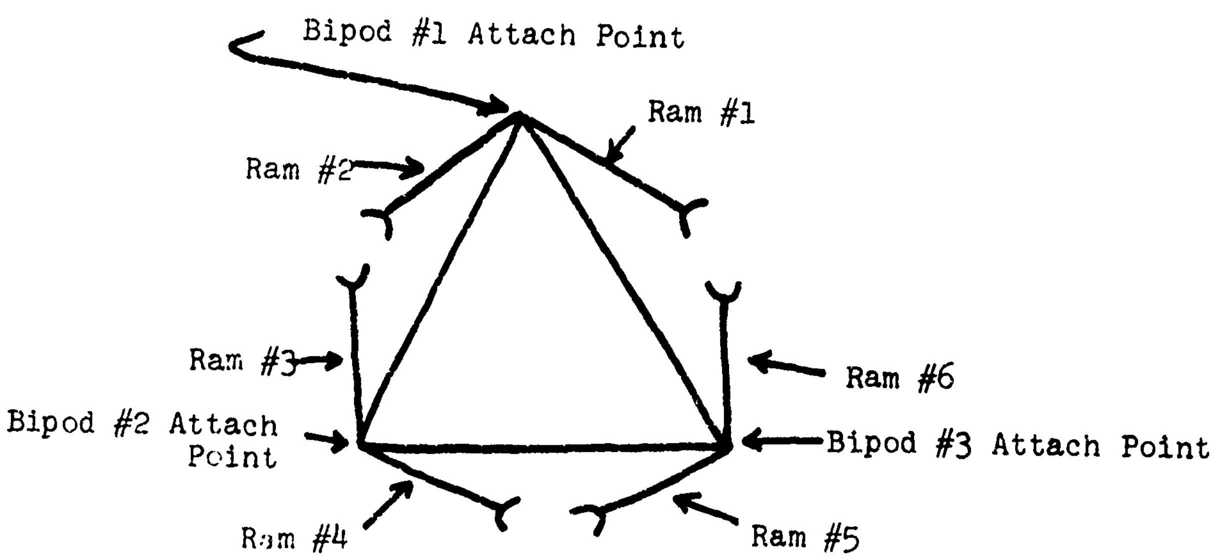

Figure 21. MOTION PLATFORM RAM AND BIPOD ATTACH POINT NUMBERING

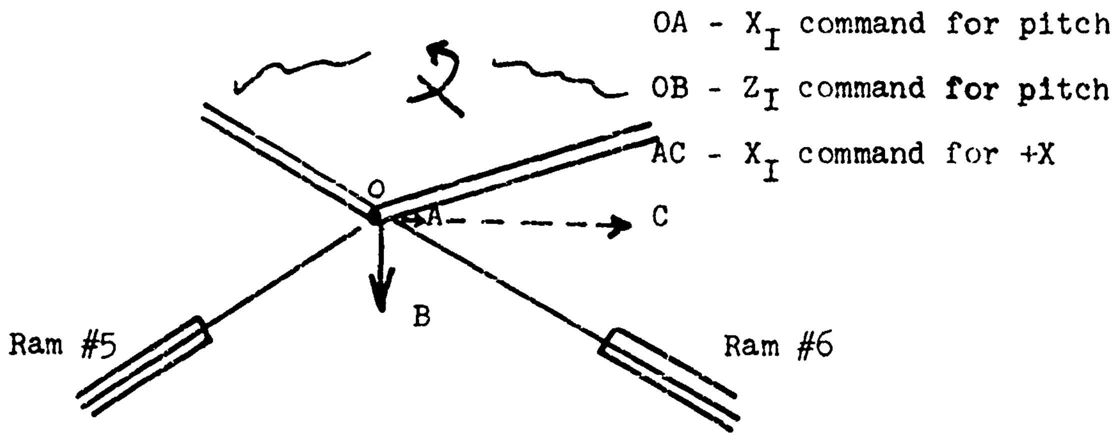

Figure 22. BIPOD ATTACH POINT POSITION COMPONENTS DUE TO PLATFORM LONGITUDINAL AND PITCH MOTION

For instance, it is now possible for us to consider how the ram commands for leg 5 and 6 are formed for a combined pitch up and +X (forward) maneuver, and the rams must then assume the position shown in figure 23.

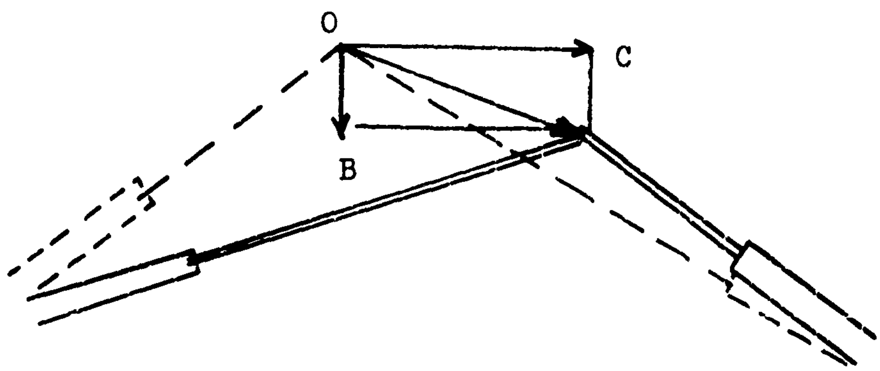

Figure 23. BIPOD ATTACH POINT MOTION DUE TO PLATFORM LONGITUDINAL AND PITCH MOTION

Now if we begin to build a conceptual diagram, the preceding procedures would appear as in figure 24.

The block identified as "upper bipod attach point I frame coordinates" represents the maintenance (hence the digital world "feedback" storage of $\underline{R}_{PB_n}$) of the I frame vector components of the bipod attach points. The vectors here are referenced to an origin defined and fixed when the platform is at the neutral point. The components of this origin are known with respect to the bottom of each ram, therefore the components of the upper end of the ram with respect to the bottom, $\underline{R}_{CYL_n}$, are available and used to determine change in ram length, ΔL_{P_n}, which is output to the linkage. It should be noted that the bulk of the ASUPT motion programs are operated at 7-1/2 iterations per second, however, the change in ram length is separated into four equal segments and output to the linkage at 30/sec for the purpose of ensuring smoothness.

The fact that the position of the bipod attach points is known also with respect to the center of the platform plane ($\underline{R}_{P_I}$) permits determining by triple cross product, the platform attitude and direction cosines relating that attitude to the I frame.

Leaving the platform, translationally speaking, at the neutral point for a moment, we have discussed two concepts which cause platform rotation: the rotational cue scheme and the gravity align scheme. Because each of these concepts alters platform attitude and both of these concepts are founded on aircraft body axis inputs (aircraft rotational rates, aircraft external forces respectively), it is necessary for both of these concepts to convert body axis rates to platform Euler angle rates to compensate and account for the platform attitude contribution of the other. Hence, in figure 25 we see platform Euler angle inputs to both of these schemes. Likewise, we see the basic data input, $\underline{W}_A^T$ and $\underline{G}_I$ to both schemes as well as some intelligence, ROT and GA discretes, indicating whether the respective scheme should actively process the input and produce a platform attitude change or, otherwise, be deactivated and zero its output.

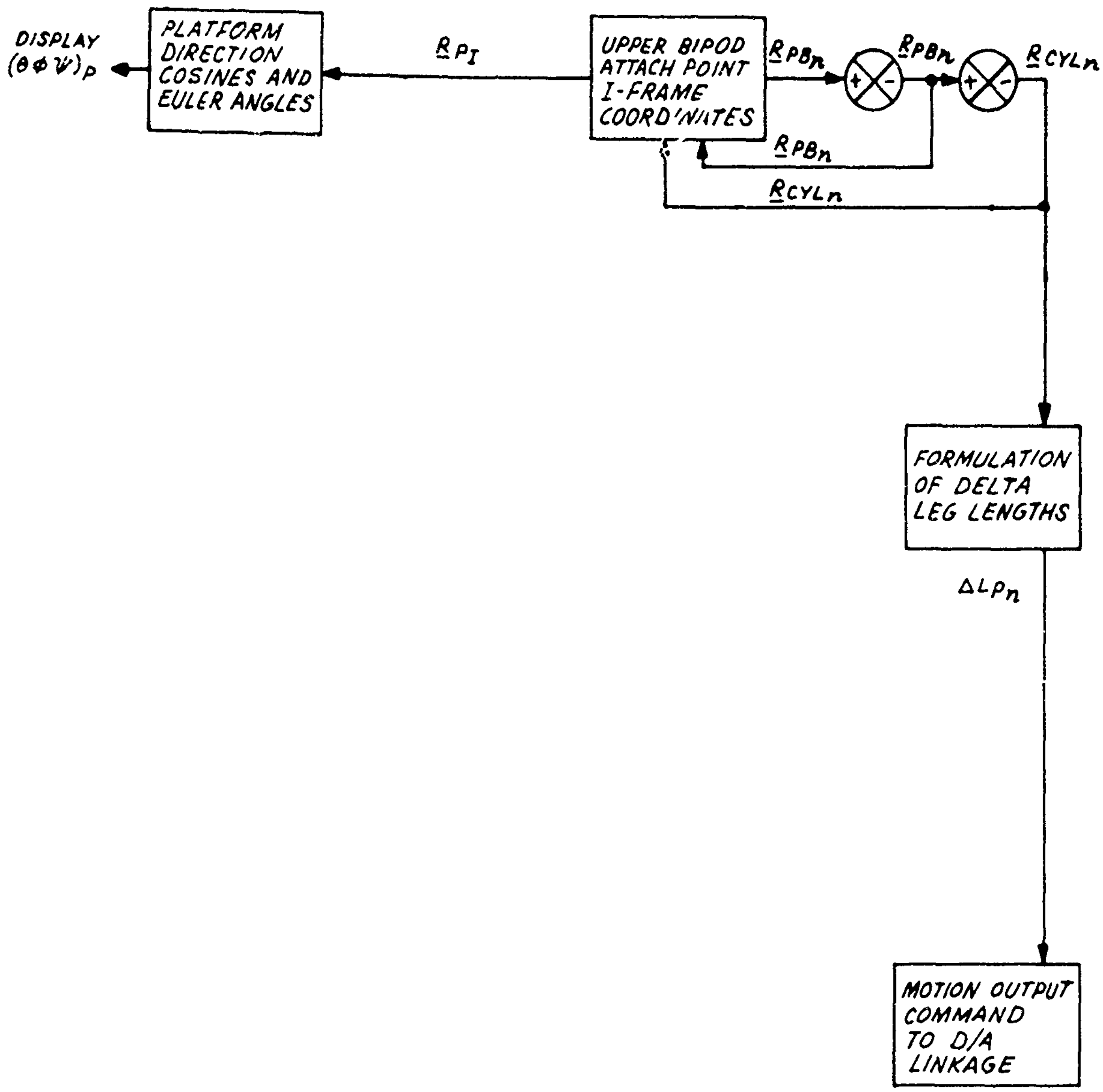

Figure 24. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART A

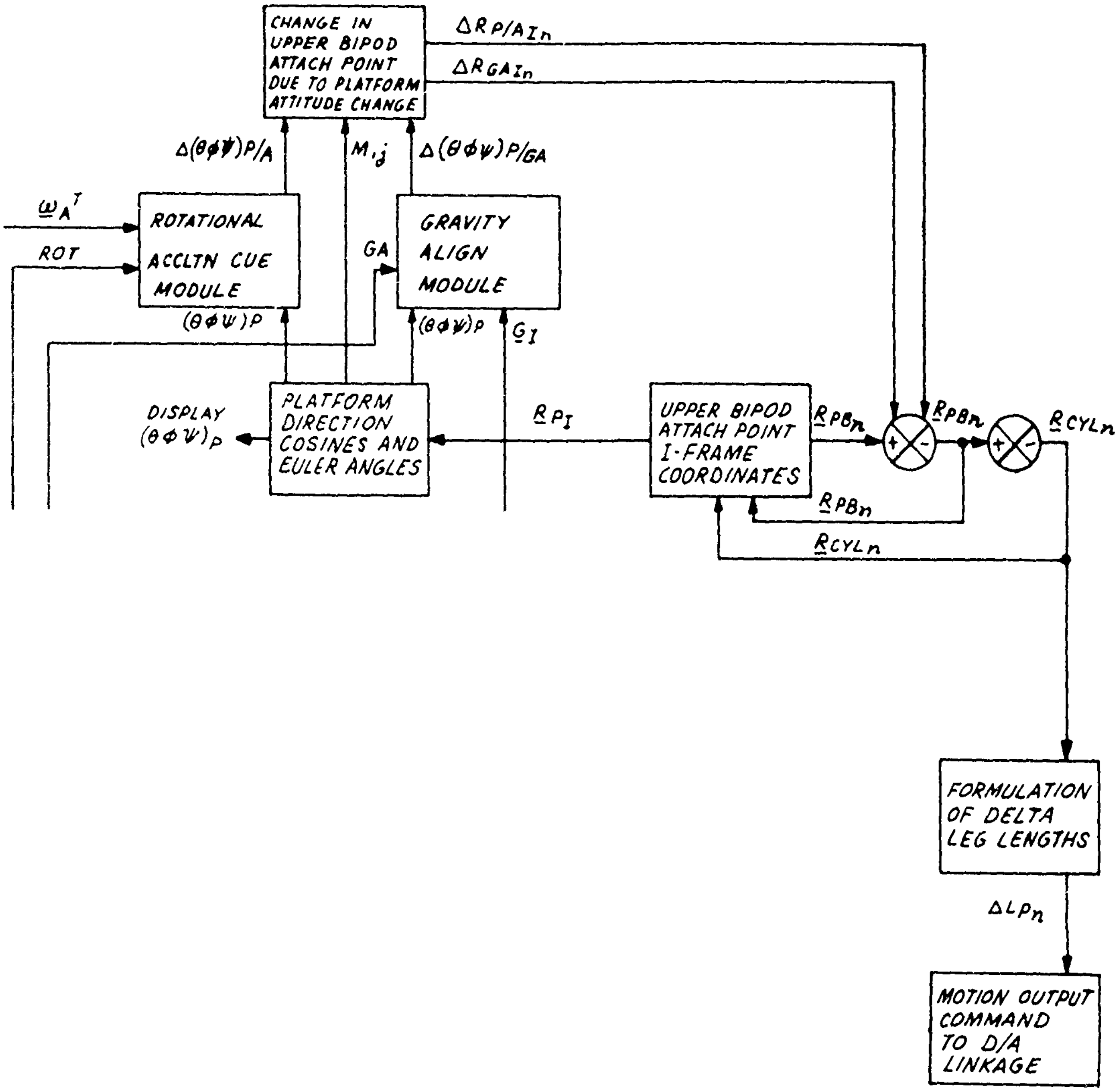

Figure 25. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART B

The outputs of each of these schemes, a demanded change in platform attitude in terms of change of platform Euler angles, forms the input to a block entitled "Change in Upper Bipod Attach Point due to Platform Attitude Change". This block contains the mathematics necessary to convert a change in platform Euler angles to an incremental change in each one of the components describing the position of the upper bipod attach point end of the six rams (routines ZSTORP and ZSTXFORM in program documentation). These outputs are summed with the current upper bipod attach point components to determine the new position. By way of example, this routine produces the OA and OB components of pitch in our earlier example. It should be noted that one of the primary reasons for operating in an incremental form rather than absolute form for Euler angle change is due to the convenience afforded by the incremental form in zeroing out the contributions to total platform attitude of a given concept.

Now turning to the translational acceleration contribution to change in upper bipod attach point position: the reader will recall that the translational concept operates on the basis of computing and summing incremental change in acceleration to build an acceleration profile. Referring to figure 26, this is seen to occur at the block entitled "Translational Accltn Δ G Module" where pilot station translational input G_{A_X}, G_{A_Y}, and G_{A_Z} are input and an I frame incremental change in acceleration is output. By immediately converting and maintaining the increments in the non-rotating I frame, we prevent the occurrence of incremental change due to platform rotation. Also, since the resultant platform positional changes are desired in the I frame, it will be convenient to consider all our translational computations in the I frame.

Since the Δ G module is building the profiles, it is in an excellent position to determine whether they are worthy, based on the considerations we have discussed within this concept, of display by the platform. TGO, the result of this consideration, can be set by this module. TGO can be set under other considerations, too. For instance, under certain conditions such as the knowledge that washout is in process, a reverse cue might be extant. Consequently the Δ G routine must supply the $\Delta \underline{G}_{I_C}$ acceleration increments to the reverse cue module for its consideration.

The reverse cue module, given the knowledge that washout is in process (WO) and the vectorial direction which would aid said washout, $(\hat{\underline{V}}, \hat{\underline{P}})$, will employ $\Delta \underline{G}_{I_C}$ to determine if a

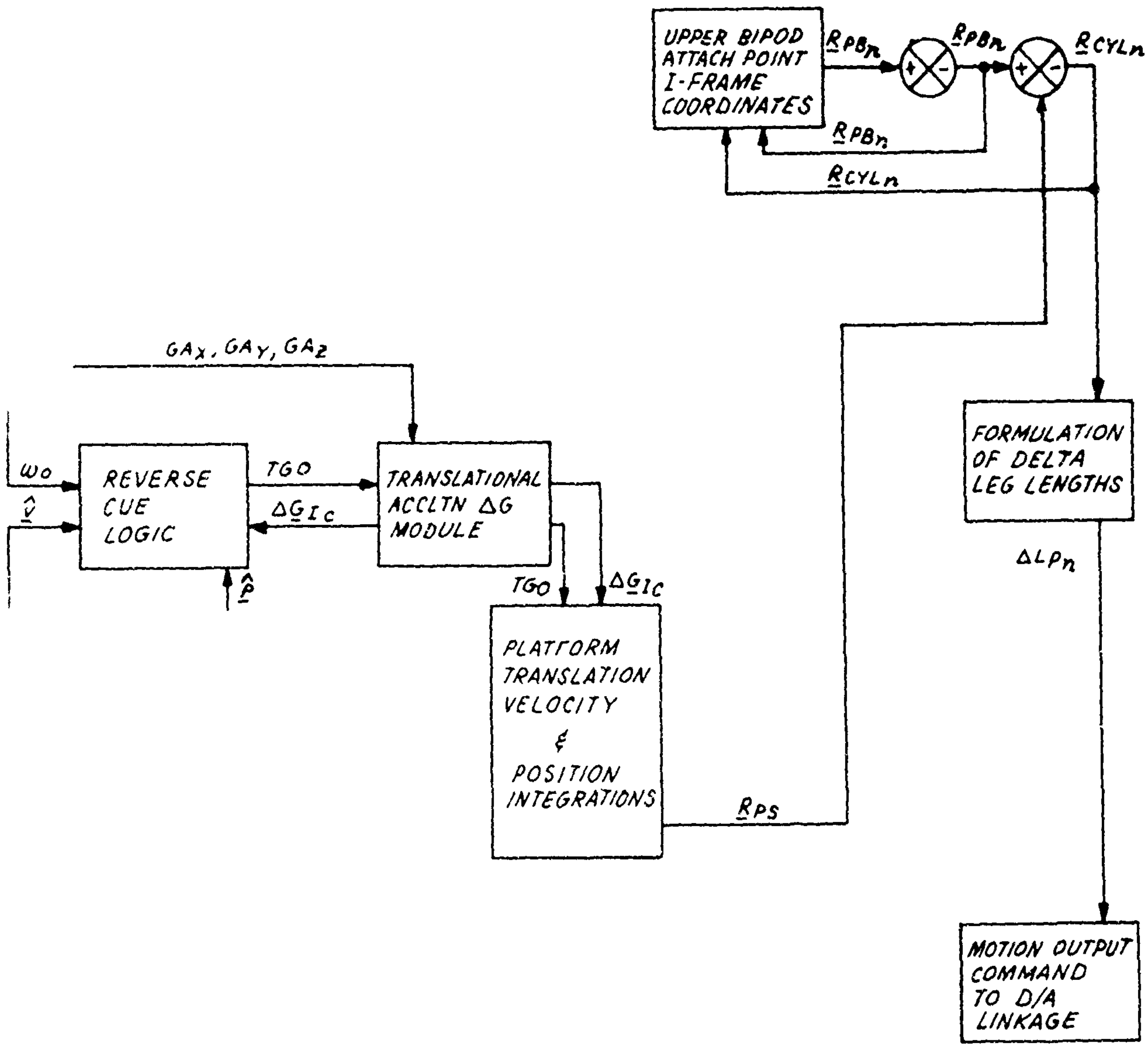

Figure 26. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART C

reverse cue can be displayed and so set TGO for the translational ΔG module. If TGO is set true (continue the translational cue), the resultant incremental acceleration must be added to the current acceleration. This result must then be integrated to velocity and position by the block entitled "Platform Translational Velocity and Position Integrations". Not only will this set of integrations accept translational acceleration cue acceleration and integrate it to platform position but it will also accept platform acceleration required by the washout routines and likewise integrate it to platform position. In any event, the result, platform I frame position components, is output to be summed with the change in upper bipod attach point position resulting from platform attitude maneuvers. This output is comparable to the AC component of our earlier example.

The reader will recall that when system capability is exceeded during the display of a translational acceleration cue, the cue is terminated and velocity and position washout initiated. Referring to figure 27, we can now insert the washout modules in our conceptual diagram of the mechanics of the program.

First, some intelligence source sets TGO false and, in doing so, initiates a call to velocity washout as given by the "call" notation. But velocity washout requires current platform velocity, $\dot{\underline{R}}_{PS}$, to establish its profile and receives this from its storage place in the "integration" block. Velocity washout establishes its profile and commences to feed back required platform acceleration, $\ddot{\underline{R}}_{PS}$, to the integration block for integration and implementation of the washout profile via the positional output, $\underline{R}_{PS}$. Meanwhile, velocity washout advises position washout of its status (either in progress or complete), via PPWO, for immediately after the velocity washout profile is completed the position washout profile will commence. The position washout module operates in much the same fashion by accepting current platform position from the integration block and using this to establish its profile and then returning accelerations, $\ddot{\underline{R}}_{PS}$, necessary to implement the washout. It in turn keeps velocity washout advised of its status via PWO. As mentioned earlier, both routines are responsible for advising reverse cue of the direction of required washout ($\underline{V}$, $\underline{P}$).

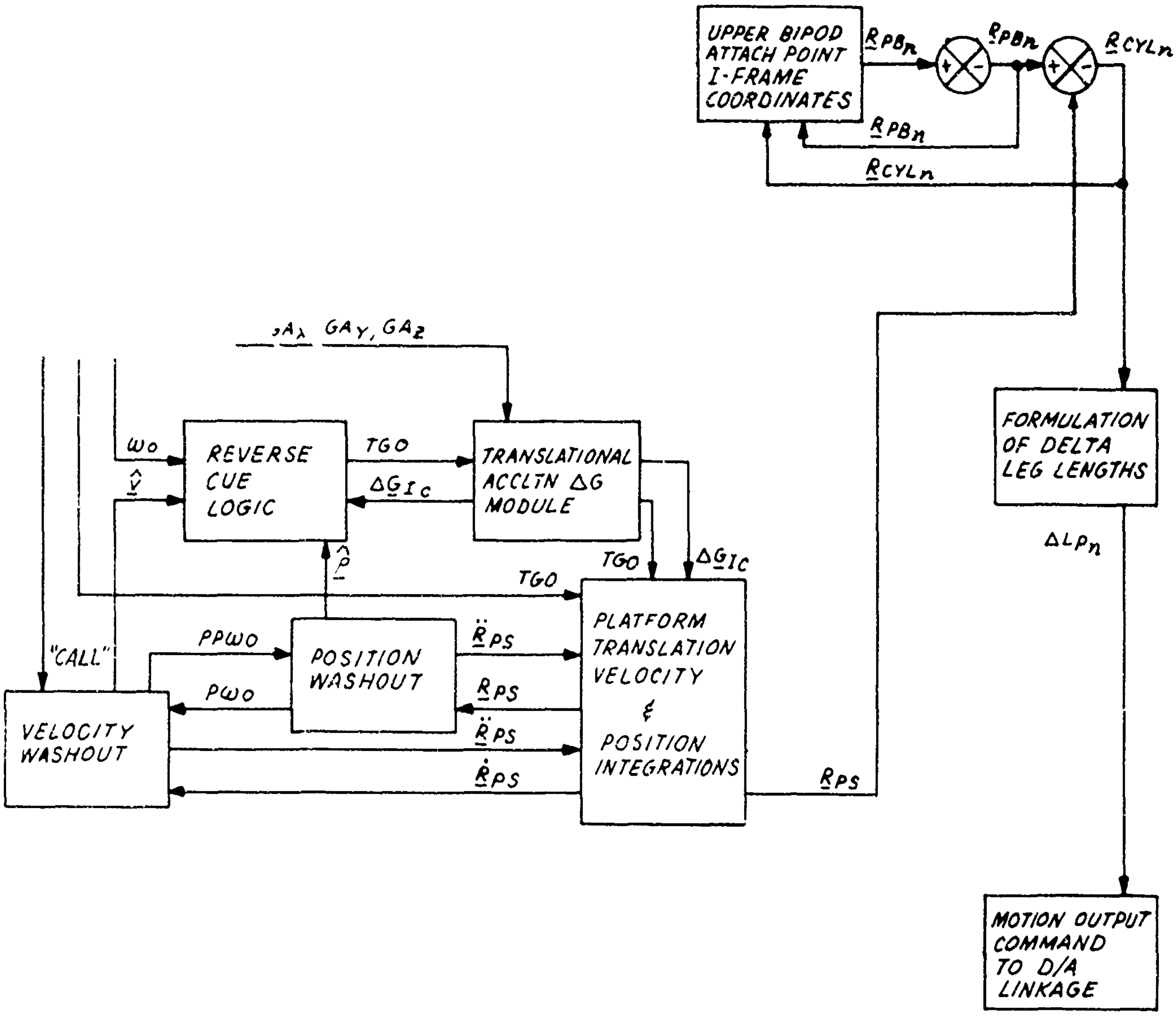

Figure 27. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART D

We have discussed the preceding conceptual mechanization in terms of some governing "intelligence factor" which would dictate whether translational cues, rotational cues and gravity align would be active or inactive. As discussed earlier in this report, these decisions are effected based on system capability violations in terms of available ram length and velocity. Figure 28 reflects the implementation of the decision making capability.

At the heart of this process is establishing the status of the flags LTGO and VTGO which, respectively, reflect the status of all six rams excursion-wise and velocity-wise.

Any ram found violating its excursion bounds causes LTGO to be set false. Any ram found violating the maximum permitted ram velocity capability will cause VTGO to be set false. The "finder" in both cases is the block entitled "Leg Length Criteria Module". It simply compares ram excursion and velocity commands against a preset maximum. Less obvious is how the ram excursion and velocity data is generated.

Considering ram length first: contained in the term $\underline{R}_{CYL_n}$, which is total ram length for the nth ram, is the last frame's ram length plus the present computational frame's contribution of rotational cue ($\Delta R_{P/A_{In}}$), gravity align ($\Delta R_{GA_{In}}$), and translational acceleration cue as integrated into position $\underline{R}_{PS}$, providing all these concepts are activated by the cue composition logic. To $\underline{R}_{CYL_n}$ is summed the positional excursion, $\underline{R}_{T_1}$, required to completely washout current platform velocity, $\dot{\underline{R}}_{PS_T}$. Since a prior knowledge of acceptance without system capability violation is not known, for the time being this velocity is known as a trail value - hence the subscript "T". $\underline{R}_{T_1}$, or the position required to wash out platform velocity, is generated at the block entitled "Positional Prediction for Velocity W/O" and is based on an analytical solution of one or the other (sine or square wave) velocity washout acceleration profiles. Essentially the time to complete the profile is computed based on the magnitude of $\dot{R}_{PS_T}$ and is represented symbolically on our diagram as $t_{V_{WO}}$ and then multiplied by average velocity during the washout to produce $\underline{R}_{T_1}$.

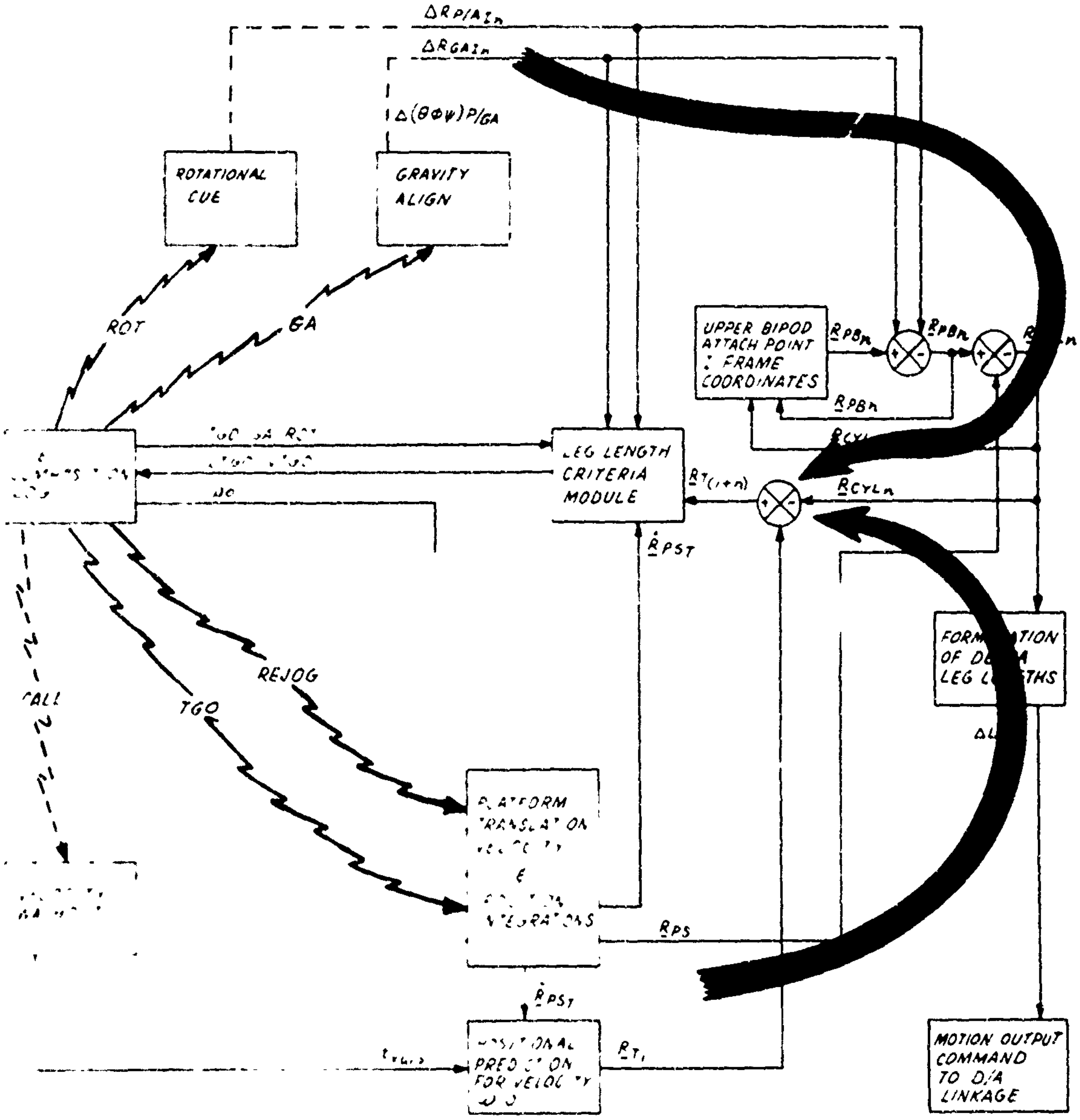

Figure 28. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART E

The sum of $\underline{R}_{T_1}$ and $\underline{R}_{CYL_n}$, $\underline{R}_{T(1+n)}$, is used as the ram length to be compared against permitted ram excursion in the leg length criteria block. The result will dictate the status of LTGO. Likewise, it is necessary to sum all the velocity contributors to ram velocity. Here again, if all concepts are active, we can expect rotational cue, gravity align, and translational cues to contribute to ram velocity. The cue composition logic issues TGO, GA, and ROT to inform the leg length criteria module which concepts are active and consequently how to perform this summation. The translational velocity of the platform, $\dot{\underline{R}}_{PS_T}$, again the trial value, is readily available for the summation and is already a velocity term. The rotational cue contribution ($\Delta R_{P/A_{In}}$) and the gravity align contribution ($\Delta R_{GA_{In}}$) are only increments for this frame and must be divided by frame time or quadrature interval to produce a velocity by "first past differences" approximation. The result, of course, is ram velocities which are selectively summed according to the status of TGO, GA, and ROT. The status of VTGO is then determined by comparison against maximum permitted ram velocity.

Now LTGO and VTGO are shipped to the cue composition block and a circular process begins. The author wishes to stress the word "circular" because he believes that not many understand that we, computationally speaking, are going to go around and around in a loop until the cue composition logic can produce a set of conditions wherein the leg length criteria return LTGO and VTGO both set true under cue conditions or, if this is impossible, permit only the washout schemes to operate until such time VTGO and LTGO become true indicating that system capability is regained.

If all cue sources were active, TGO, GA, and ROT are true, and LTGO and VTGO return true, the cue composition logic will permit the resultant ram lengths to be commanded and consequently the trial value of platform velocity, $\dot{\underline{R}}_{PS_T}$ will become the accepted value of platform velocity, $\dot{\underline{R}}_{PS}$, and there will be no additional comparisons required until the next frame. However, if VTGO returns false indicating a velocity violation, the cue composition logic advises the translational velocity and position integrations block to reintegrate this frame's translation acceleration but eliminate the current frames $\Delta\underline{G}_{I_C}$ acceleration increment.

In other words, back off one frame's incremental acceleration and come up with a new $\underline{R}_{PS}$ position and $\dot{\underline{R}}_{PS_T}$ velocity. Obviously a new $\underline{R}_{CYL_n}$ and $\underline{R}_{T(1+n)}$ must be computed, and LTGO and VTGO recomputed.

Now if VTGO doesn't return to the true state indicating ram velocity within limits or if LTGO is false, indicating a ram excursion violation at the end of the upcoming velocity washout profile, the cue composition logic deactivates the translational cue by setting T O false. This, of course, activates the velocity washou profile and since the acceleration cue is now terminated, a smaller value of $\underline{R}_{PS}$ translational position will result. This of course translates into a more palatable $\underline{R}_{CYL_n}$. Now $\underline{R}_{T_1}$ and $\underline{R}_{T(1+n)}$ are not even computed because the translational cue was terminated in time to prevent a positional excursion violation at the conclusion of velocity washout. $\underline{R}_{CYL_n}$ is directly input to the leg length criteria in hopes of returning with true values of LTGO and VTGO.

It is possible, however, that the above abandoning of the translational cue will not cause LTGO and VTGO to return true. In this case we are not yet finished with our computations. The cue composition logic next deactivates the gravity align scheme by setting GA false, extracts the gravity align contribution, $\Delta R_{GA_{In}}$, from $\underline{R}_{CYL_n}$ and tries the leg length criteria block once again in hopes of receiving LTGO and VTGO true.

Even deactivating gravity align may not do the trick, and if either LTGO or VTGO return false, the cue composition logic will deactivate the rotational cue generation scheme as well. ROT is set false; the rotational cue contribution $\Delta R_{P/A_{In}}$, extracted from $\underline{R}_{CYL_n}$, and what is left, of course, is just the washout contribution to platform position and velocity. This value of $\underline{R}_{CYL_n}$ becomes, finally, the commanded ram length and the frame's computations are completed.

As the washout profiles operate on succeeding frames, system capability will return and LTGO and VTGO will eventually return true. However, should there be rotational cues to be displayed or gravity align to be performed on the very next frame, these two routines will reset ROT and GA to true for the cue composition logic and will cause leg length criteria module testing to recommence. TGO, on the other hand, can only be set true by the reverse cue logic during the washout period; consequently, unless a reverse cue comes along, TGO and its significant impact on system capability, will not be apparent until system capability is again present via completion of the washout profiles.

The author has belabored the preceding decision making process somewhat because if the reader comprehends this ability, as well as the importance in the vectorial summation, to determine upper bipod attach point position, he is in an excellent position to grasp the overall mechanization concept. The reader should then be able to integrate the individual concepts we have been discussing. Putting the pieces together on our conceptual diagram we arrive at figure 29.

Here we see nearly the complete mechanization in terms of some rotational velocity input, $\underline{W}_A^T$, translational acceleration input, G_{AX}, G_{AY}, G_{AZ}, and a buffet input called BUMPY. There remains only a small discussion on how these inputs are to be made available to the motion program.

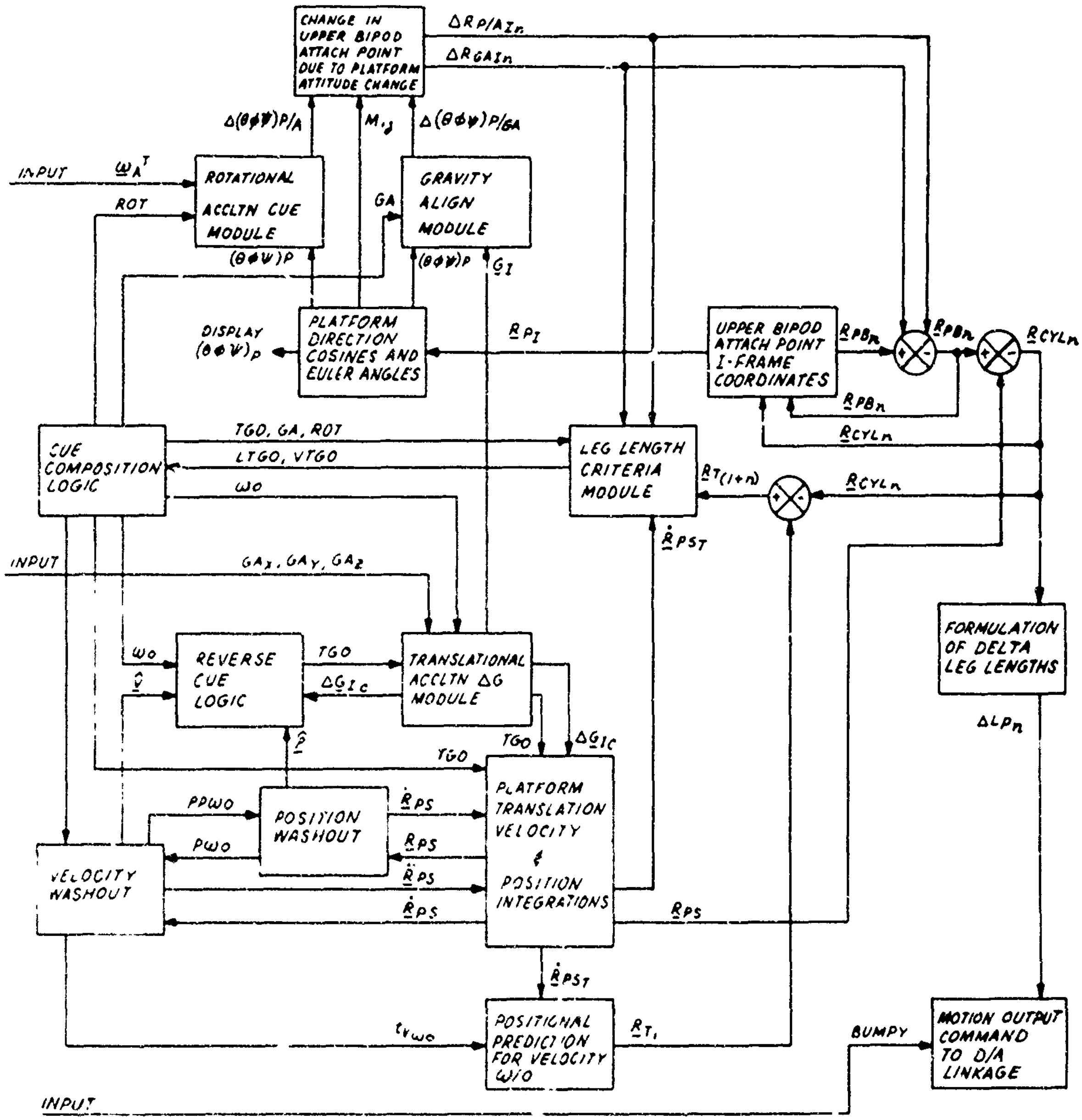

Figure 29. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART F

Consider now figure 30. The inputs to the motion program are processed herein. First, the reader will recall the discussion of the special effects package. The inputs for this package are delivered by flight software directly, and the square wave output or pulse is forwarded to both the G seat program as well as the motion linkage buffet D/A. The output of this D/A is input to the hydraulic servo in each of the six rams.

All the other inputs are processed by an interface program which simply is a "load-store" program. This is done to permit the motion program to be separated from flight acceleration inputs and operated with a series of test inputs of known shape, amplitude, direction and frequency. This capability is useful in initial set-up as well as periodic maintenance.

The outputs of the interface module are the aircraft body axis (C. G.), translational accelerations ($\underline{A}_A{}^T$), rotational accelerations ($\dot{\underline{W}}_A{}^T$), and rotational rates ($\underline{W}_A{}^T$). These are used in transferring the accelerations to the pilot's position to determine induced translational acceleration (G_{A_T}) which is output to the G seat program. These accelerations are processed once again to eliminate the effects of the lateral offset associated with the pilot's position from the XZ plane of aircraft symmetry. The resultant accelerations, flight deck accelerations (G_{A_X}, G_{A_Y}, G_{A_Z}), form the translational acceleration input to the motion module.

Rotational rates are made available to the rotational acceleration cue scheme directly. In addition, the interface module provides the G seat program with attitudinal and roll rate/acceleration inputs unique to the G seat program.

This completes our discussion of the mechanization of motion concepts. The final conceptual diagram, figure 31, represents the integration of all the concepts introduced herein.

NOTES: ‡ RECEIVE FROM FLIGHT - RANDOM #, BUFFET, SPD BRAKE EXTENSION, GEAR NOT DOWN, GEAR NOT UP, A/C VELOCITY, WEIGHT ON WHEELS

* RECEIVE FROM FLIGHT - TRANSLATIONAL ACCLTN COMPONENTS, ROTATIONAL ACCLTN AND VELOCITY COMPONENTS, A/C C.G. LOCATION, ℓ_3, M_3, n_3 DIRECTION COSINES

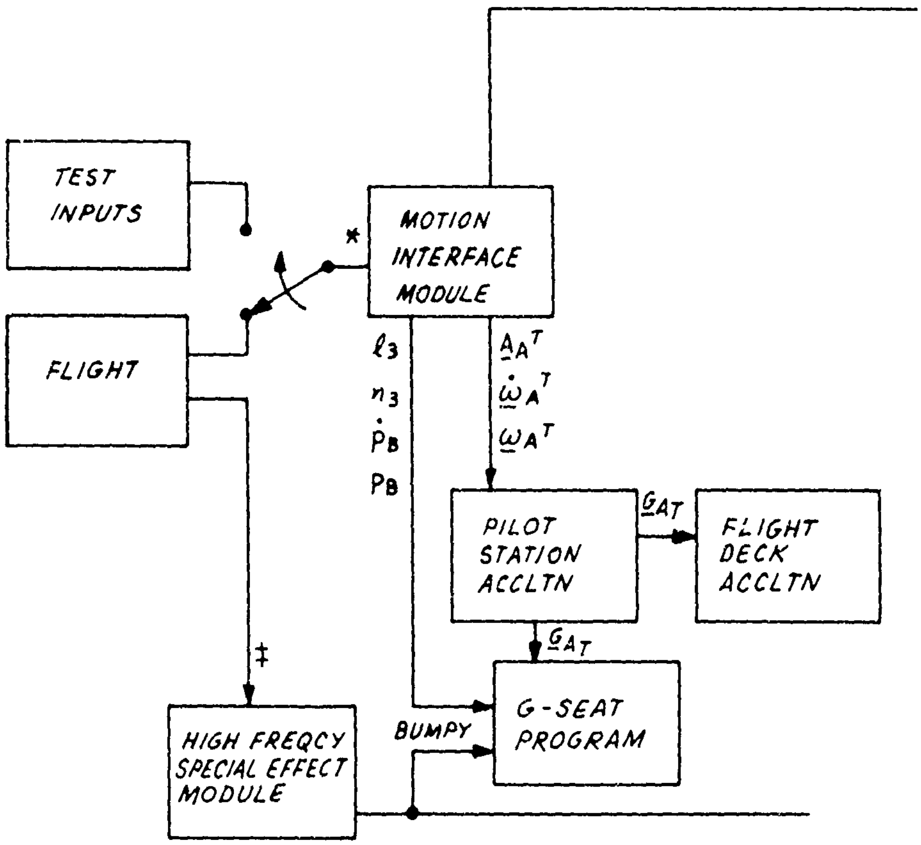

Figure 30. MOTION SYSTEM CONCEPTUAL DIAGRAM - PART G

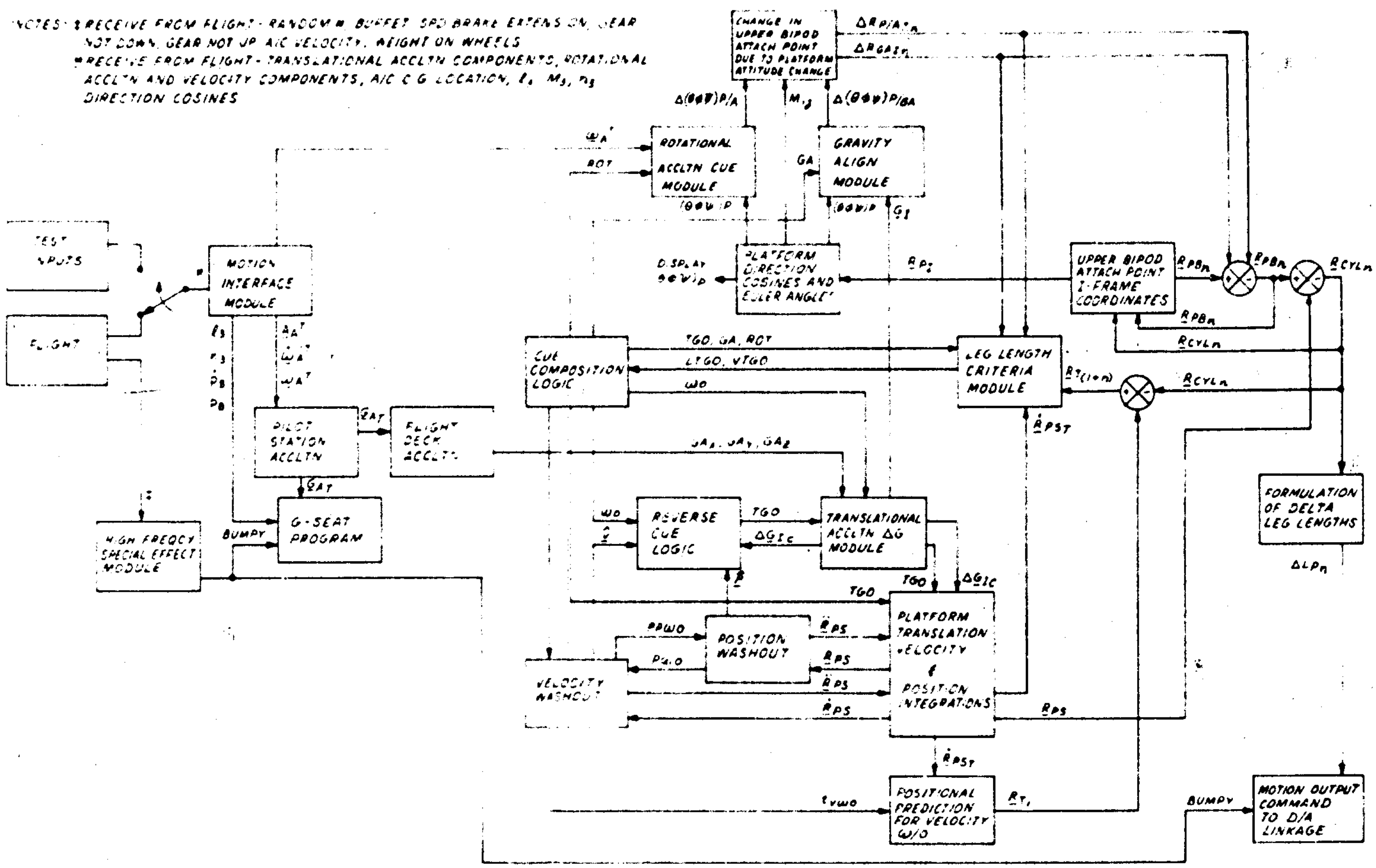

Figure 31. MOTION SYSTEM CONCEPTUAL DIAGRAM

ASUPT RESEARCH CONTROL

At various points in the preceding discussions we have mentioned experimentor control of the motion system. This concluding section of the Motion System Technical Report will deal, in brief form, with the CRT control of motion system experimental parameters. This section should provide the reader with an understanding of what parameters are available for alteration, where they are located, and also, when taken in the context of the concepts in which they are employed, the impact of alteration. For this reason the reader is urged to read the following section with continued reference to our earlier conceptual discussion.

The format of the experimental parameters is depicted on the following hard copy of the "Motion Mod" CRT pages 2 (figure 32) and 3 (figure 33). These hard copies were taken during final on-site HSI, 20 February 1974. It is the author's belief that the numerical settings reflect those existing at acceptance in all but one or two cases.

Considering page 2 first (figure 32):

The velocity and position washout max acceleration constraints refer to the acceleration profiles used in washout. These two parameters establish the maximum magnitude of acceleration displayed during the washout process. Increasing these values shortens the period of washout and increases cue duration.

The gravity align constants include the maximum permitted rotational acceleration and velocity to be employed in altering platform orientation and consequently the apparent direction of the gravity vector. The reader will recall both of these parameters must remain subliminal. Also included is the nominal amount of platform reorientation (pitch-roll combination) to be devoted to gravity align. Remember however, that this is not an absolute dedication for if the rotational cue scheme requires additional excursion it will take it from gravity align. Lastly, to prevent hunting, a deadband is established so that the external force vector (that which must be rotated into the gravity vector) must move a preset distance away from the gravity vector prior to commencing platform gravity align reorientation.

The reader will recall from the description of rotational cue concepts thatthe poles of the digital shaper used for all three rotational axes may be altered, thereby changing the response characteristics of the rotational cues. The author advises care in altering the poles. Before altering

COCKPIT A	MOTION VARIABLE CONSTANTS (05-02)	COCKPIT B	
	I. WASHOUT PROFILE CONSTANTS		
01	VELOCITY WASHOUT MAX ACCELERATION (G' S)	41	.02999
02	POSITION WASHOUT MAX ACCELERATION (G' S)	42	.00999
	II. GRAVITY ALIGN CONSTANTS		
03	ROTATIONAL ACCELERATION (DEG/S/S)	43	.1199
04	ROTATIONAL VELOCITY LIMIT (DEG/S)	44	1.500
05	MAX PLATFORM ROTATION (DEGREES)	45	6.000
06	DEAD BAND FOR MIN ROTATION (DEGREES)	46	.0999
	III. ROTATIONAL CUE CONSTANTS		
	A. SHAPING FILTER POLES		
07	POLE # 1 (RAD/SEC)	47	-2.000
08	POLE # 2 (RAD/SEC)	48	-1.000
	B. SHAPING FILTER GAIN		
09	ROLL CHANNEL	49	.1999
10	PITCH CHANNEL	50	.3999
11	YAW CHANNEL	51	.1249
	IV. TRANSLATIONAL CUE SHAPING		
	A. PHASE MODIFICATION		
12	LEAD-LAG TIME INTERVAL (SEC)	52	000000000
	B. ACCELERATION ATTENUATION		
13	LONGITUDINAL (0 TO 1)	53	.2499
14	LATERAL (0 TO 1)	54	.2999
15	VERTICAL (0 TO 1)	55	.2999
	C. JERK ATTENUATION FACTORS		
16	LONGITUDINAL (0 TO 1)	56	1.000
17	LATERAL (0 TO 1)	57	.4999
18	VERTICAL (0 TO 1)	58	.1999
	D. JERK LIMITS		
19	MAX JERK TO BE ACCEPTED (G' S/SEC)	59	1.250
20	MIN JERK TO BE ACCEPTED (G' S/SEC)	60	.0799
	E. ACCELERATION THRESHHOLD		
21	TRANSLATIONAL ACCEL H/D ONSET (G' S)	61	.0799
22	V. MOTION TEST NUMBER	62	000000000
23	PEAK VALUE OF TEST SIGNAL	63	000000000
24	SIGNAL ANGULAR FREQUENCY (DEG/S)	64	000000000
25	SIGNAL DELAY TIME CONSTANT (0 TO 1)	65	000000000
26	SIGNAL REINITIALIZATION PERIOD (SEC)	66	15.00

Figure 32. MOTION RESEARCH CRT Page 2

COCKPIT A	MOTION VARIABLE CONSTANTS (05-03)	COCKPIT B	
	VI. MOTION SYSTEM PHYSICAL CONSTRAINTS		
01	MAX PERMITTED RAM VELOCITY (IN/SEC)	41	19.00
02	MAX PERMITTED RAM STROKE (INCHES)	42	28.00
03	MAX PERMITTED ROLL (DEGREES)	43	15.00
04	MAX PERMITTED PITCH (DEGREES)	44	15.00
05	MAX PERMITTED YAW (DEGREES)	45	32.00
	VII. BUFFET CHANNEL CONSTANTS		
06	A. MAX DISPLACEMENT (INCHES)	46	1.639
	B. LANDING GEAR CUE SCALING		
07	OVERALL GEAR RUMBLE (NON-DIM)	47	.04999
08	GEAR DOWN RUMBLE (NON-DIM)	48	.00390
09	GEAR-IN-TRANSIT RMBL (NON-DIM)	49	.00781
10	GEAR BUMP (NON-DIM)	50	2.000
11	C. SPEED BRAKE RUMBLE (NON-DIM)	51	.00599
12	VIII. ACCELERATION ATTENUATION USED WHEN G-SEAT PROGRAM ACTIVE	52	1.000
	IX. SIMULATED AIRCRAFT'S DISTANCE FROM 30% MAC TO PILOT'S EYE		
13	LONGITUDINAL OFFSET (INCHES)	53	33.46
14	LATERAL OFFSET (INCHES)	54	-12.00
15	VERTICAL OFFSET (INCHES)	55	-23.50
16	X. DISPLAY RELAXATION AND ONSET CUES	56	FALSE
17	XI. ROTATION ABOUT PILOT'S EYEPOINT	57	FALSE
18	XII. MOTION TEST NUMBER	58	000000000
19	PEAK VALUE OF TEST SIGNAL	59	000000000
20	SIGNAL ANGULAR FREQUENCY (DEG/S)	60	000000000
21	SIGNAL DECAY TIME CONSTANT (0 TO 1)	61	000000000
22	SIGNAL REINITIALIZATION PERIOD (SEC)	62	15.00
23	XIII. SPECIAL MOTION CONTROL(FOR TEST)	63	FALSE
24	SPECIAL MOTION ON CONTROL	64	FALSE
25	SPECIAL MOTION-IN-TRANSIT	65	FALSE

*** CAUTION: WHEN MOTION IS ACTIVE, VERIFY THAT MOTION=FALSE AND MOTXIT=TRUE BEFORE SELECTING MOTION CONTROL=TRUE.

Figure 33. MOTION RESEARCH CRT PAGE 3

them, the experimentor should have an understanding of the response characteristics of a second order filter The pitch, roll, and yaw gains discussed in the rotational cue section appear next and may be adjusted on a per axis basis.

Within the translation cue shaping section appears a lead/lag phase modification term nominally set at zero. The range of this term is $\pm$ one quadrature interval (1/7.5 seconds) and the term serves to advance (+) or retard (-) the occurrence of both translational and rotational cue profiles. Next appears a set of attenuators which modify the flight deck translational acceleration components on a per axis basis. G-seat acceleration, motion system translational cue, and gravity align effects are all affected by the setting of these attenuators. The jerk attenuators, which appear immediately thereafter, alter the size of each additional increment of acceleration used in building the motion system translational cue acceleration profile. This set of attenuators affects only the translational cue section and are set on a per axis basis.

The reader will recall from the translational acceleration cue discussion that the acceleration profile must rise above some minimum jerk level consistent with the threshold of jerk before qualifying for display. Further, it may rise no faster than some maximum jerk level in order to guarantee, under motion system capability, some minimum cue duration. These two parameters are located under the title "Jerk Limits".

Next appears a parameter loosely termed "Translational Acceleration Without (W/O) Onset". This reflects the subliminal threshold of translational acceleration magnitude above which cue display is desired regardless of whether the minimum jerk levels, mentioned above, are broached.

The balance of the parameters on this page refer to the motion test program and are adequately described in the Motion Test Guide, ASUPT-68,[6] page 79.

Turning now to the second CRT page (figure 33):

The first two parameters refer to the oft-mentioned system capabilities of ram excursion and velocity. These two parameters are used in the leg length criteria module to determine cue acceptance and composition.

NOTE

> The second, ram excursion, is set at 27 inches rather than 28 to preclude motion system shutdowns during very violent maneuvering occurring during spins.

The next set of parameters refer to the attitudinal excursion devoted to rotational cue simulation. These are set on a per axis basis. It is the responsibility of the rotational cue gain terms to properly convert simulated aircraft rotational rates to platform attitudinal excursion such that the maximums stated here are not exceeded when maximum aircraft rotational velocity is experienced. If not, these attitudinal maximums will act as clippers.

NOTE

> Maximum permitted yaw has since been reduced to 25 degrees to accommodate the spin conditions and reflect a more reasonable value in light of simultaneous ram demands.

The next group of parameters pertain to the motion special effects package. The first establishes the maximum ram excursion command (in inches) for a special effects pulse and is used as a clipper. The overall gear rumble term attenutates or amplifies the pulses of all special effects except buffet. Within this group so attenuated or amplified, the composition may be altered by the next three parameters which serve as further attenutators/amplifiers for gear down rumble, gear in transit rumble, gear down bump, and speed brake rumble.

Next appears a single attenuator factor which is automatically employed uniformly on the components of translational acceleration when the G seat is active. Attenuation occurs on both the pilot position components used by the G seat and the flight deck components used by the motion translational scheme.

The next three parameters establish the pilot's position with respect to 30% mac as measured in the aircraft body frame. These components are used to transfer aircraft rotational and translational accelerations to the pilot's position.

The last two experimentor parameters are flags. The first, if true, establishes the desire to display acceleration profiles that are returning to the nominal 1 G state. Otherwise only acceleration profiles of rising magnitude will be displayed. The second flag, if set true, will cause platform rotational acceleration cues to be displayed about the pilot's head. Otherwise, this rotation will occur about the platform.

SUMMARY

The foregoing Technical Report has attempted to provide a foundation of knowledge to prepare the reader for examining the ASUPT motion program in greater depth. The following points stand out in the author's mind as being quite important:

1. The ASUPT motion system is designed to be a flexible model in which research concerning kinesthetic simulation may be conducted.

2. Although the system is designed with vestibular sensory system stimuli in mind, the motion system will also drive the haptic system. Motion system/G seat interrelationships can also be studied.

3. The motion system is a constrained system thereby limiting the stimuli available and consequently forming the requirement for stimulation simulation research.

4. The ASUPT concepts are but one set of concepts for motion simulation. This set was established as being worthy of investigation at the onset of the ASUPT program. Their development has been pursued to provide a system in which separate attributes may be isolated and investigated to provide kinesthetic simulation data points valid for the type of task loading associated with piloting an aircraft.

5. The mechanization of the concepts can best be understood by thinking in terms of bipod attach point positional definition and comprehending the role of the cue composition logic.

6. Simulation Products Division's experience with the ASUPT motion system, particularly during the final checkout phase,[6] has led to the belief that the rotational cueing concept embodied in the ASUPT design represents a significant advance in motion simulation. SPD is continuing to investigate this concept with an eye to broadening its applicability and refining the fidelity of the resultant drive. In this way the ASUPT motion system has already produced a worthy legacy.

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